Water resources of Wadi Hanifah, Saudi Arabia: a case study

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WATER RESOURCES OF WADI HANIFAH, SAUDI ARABIA :

A CASE STUDY

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ABSTRACT

Although Saudi Arabia has made great progress on almost all fronts, water has always been, and still is, a serious problem. Settlement in the central area of the country is concentrated in the wadis, of which Wadi Hanifah is a good example.

The Wadi descends through the central slope of the Tuwaig mountain, where Jurassic units predominate, and ends in the Al-Kharj Plain, where Cretaceous deposits outcrop.

Climate is influenced to a limited extent by the relatively high altitude of the Tuwaig mountain, especially where rainfall is concerned, and an annual average of 100 mm is recorded. The rate of evaporation, however, is very high, because of the cloudless sky and high temperatures.

Run-off occurs only after torrential rain, when the Wadi collects flood water from its many tributaries. Seven dams have been built in recent years in an attempt to increase underground recharge.

The volume, quality and locations of underground water are determined almost entirely by climatic regime and geological characteristics. Fractions and cavities in the Jubaila limestone around Riyadh, and the alluvium deposits in the Wadi's channel used to be the main water sources. Water in these aquifers used to be at an easy reach at a depth of about 10 m beneath the surface. Urban expansion of Riyadh City, however, required a continual increase in water extraction, and the introduction of modern equipment in agriculture also increased water consumption. This led to the lowering of the alluvium aquifer on the one hand, and the contamination of the Jubaila limestone aquifer on the other.

The tapping of the Minjur aquifer in 1956 at a depth of more than 1,000 m temporarily solved the problem, but as the discharge increased sharply water level fell to a considerable depth, and in the meantime the alluvium aquifer continued dropping, so that in some areas water has been almost completely depleted.

It is obvious that the lack of control over water use, and the shortage of adequate investigation and experience, combined with the many different authorities in charge of water, produced a careless attitude to this valuable resource in both urban life and agriculture.

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LIST OF ABBREVIATIONS

AH	After Hijrah (Islamic Calendar)
cm	centimetres
cu m	cubic metres
E	East
etc.	et cetera
i.e.	that is
km	kilometres
m	metres
mm	millimetres
N	North
pl.	plural
ppm	parts per million
sq km	square kilometres
sq m	square metres
l/s	litres per second
TDS	Total Dissolved Solids

ARABIC NAMES

Abalkbash	أبالكباش
Ad-Dahna *	الدهناء
Ad-Dir'iyyah	الدرعية
Ain Ad-Dhil'a *	عين الضلع
Al-Aflaj *	الأفلاج
Al-Ahaisi Group	مجموعة الأحيسى
Alaisan	أليسن
Al-Artawiyyah *	الأرطاوية
Al-Aramah *	العرمة
Al-Badi'ah	البديعة
Al-Bat'ha	البطحاء
Al-Elb	العلب
Al-Erdh	العرض
Al-Farazdag	الفرزدق
Al-Ghat	الغاط
Al-Ghithwanah	الغذوانة
Al-Gurashiyyah	القرشية
Al-Ha'ir	الحائر
Al-Hautah *	الحوطة
Al-Hisyan	الحسيان
Al-Hutay'ah	الحطيئه
Al-Jubail *	الجبيل
Al-Jubailah	الجبيله
Al-Kasseim	القصيم
Al-Kharj *	الخرج
Al-Kulleyyah	الكلية
Al-Majma'ah *	المجمعة
Al-Mirba'aniyyah	المربعانية
Al-Manscuriyyah	المنصورية
Al-Masan'i	المصانع
Al-Ma'ther	المعذر
Al-Mughaider	المغيدر
Al-Murabba'a Palace	قصر المربع

Al-Muzahimiyyah *	المزاحمية
Al-Thumairi Gate	بوّابة الثميرى
As-Safat	الصفاة
As-Sayf	الصيف
Ash-Shafa	الشفاء
Ash-Shumaissi	الشميسى
As-Sulayyel *	السليّل
As-Suwaidi	السويدي
At-Tawdheyyah	التوضحيه
Al-Uraija	العريجاء
Al-Uyaynah	العيينه
Al-Washm *	الوشم
Al-Wasm	الوسم
Bani Hanifah	بنى حنيفه
Bir Sidiriyyah *	بئر السديرية
Bir Tabrak *	بئر تبرك
Boudhah Group	مجموعة بوضة
Dahl Heit *	دحل هيت
Dhruma *	ضرماء
Dirab	ديراب
Dukhnah	دخنه
Ergah	عرقة
Gharb	غرب
Great Nafud *	النفود العظمى
Guway'iyyah *	القويعية
Hanifah	حنيفة
Hajr	حجر
Haradh *	حرض
Hisyan	الحسيان
Hith Anydrite	تكوين هيت
Huraimela *	حريملاء
Jabal Al-Abakkayn	جبل الأبكين
Jabrah	جبره
Jilh Formation	تكوين جله

Jiza	جزعة
Jubaila Limestone	تكوين الجبيلة
Khafs Dighrah *	خفس دغره
Kah't	قحط
Khareef	خريف
Khash Al-Baladiyyah	خشم البلدية
Khashm Al-Khalta *	خشم الخلطاء
Khashm Mawan *	خشم ماوان
Khashm Midhya'ah *	خشم مضياعة
Khashm Musaigerah *	خشم مصيغرة
Liban	لبن
Marat S38 *	مراة س ٣٨
Marrat Formation *	تكوين مراة
Minjur	المنجور
Nafud Ad-Dahi *	نفود الدحي
Nafud As-Sir *	نفود السر
Nafud Kunaifithah *	نفود قنيفذة
Nejd	نجد
Rij'an	رجعان
Riyadh	الرياض
Riyadh-Taif Highway	طريق الرياض الطائف
Rub al Khali *	الربع الخالي
S'iah	صياح
Salam	سلام
Salboukh	صلبوخ
Sanyah	سانيه
Shat Al-Arab *	شط العرب
Sodous *	سدوس
Sulaiy Formation	تكوين السلي
Tuwaig Mountain	جبل طويق
Tuwaig Formation	تكوين طويق
Um Al-Hamam	أم الحمام
Uraidh	عريض

Wadi Alaisan	وادي اليسن
Wadi Ad-Dawsir *	وادي الدواسر
Wadi Al-Ammariyyah	وادي العمارية
Wadi Al-Buayja	وادي البعيجاء
Wadi Al-Haddar *	وادي الهدار
Wadi Al-Kabeir	وادي الكبير
Wadi Al-Khomrah	وادي الخمرة
Wadi Ghalah	وادي غالة
Wadi Ghubairah	وادي غبيره
Wadi Ha	وادي حاء
Wadi Hanifah	وادي حنيفه
Wadi Hareiqah	وادي حريقة
Wadi Hinow *	وادي حنو
Wadi Huraymila *	وادي حريملاء
Wadi Liban	وادي لبن
Wadi Nimar	وادي نمار
Wadi Ar-Rummah *	وادي الرمّه
Wadi Sir	وادي سر
Wadi Sofar	وادي صفار
Wadi Wasit *	وادي واسط

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* Outside the area under study.

CHAPTER ONE

INTRODUCTION

Water is a vital resource in any part of the world, but it is a particularly important factor in arid lands such as the central part of Saudi Arabia and has a great impact on the way of life and the location of settlements. Shortage of water has played a primary role in determining the type of farming and size of cropped areas in the region. Indeed, it was the lack of water which was the main cause of people leaving their homeland, seeking an easier life in places like the Arabian Gulf States or even as far afield as North Africa and India. At present, many families have settled in Kuwait, Bahrain, Syria, Egypt and India, whose forefathers originated from Nejd - Central Arabia, and these families still have strong links with their relatives in the region (Wahbah, 1946). In Bedouin communities, the conflict which used to arise in the past over priority in obtaining water from an isolated shallow well caused many deaths.

Over the last half-century, the socio-economic life of Saudi Arabia has been developing rapidly, mostly as a result of two factors:

(i) The foundation in 1931 of the Kingdom of Saudi Arabia as a new, modern state, offering greater stability and security.

(ii) The potential of the oil revenue which has played a tremendous part in raising the living standards of the people.

Yet, with such socio-economic change, the problem of water supplies has become even more important, largely because of the rapid increase of population brought about by natural growth and by immigration to the expanding urban areas from rural areas and from abroad. One clear example of this is the city of Riyadh, which was described by the VBB firm (1965) as one of the fastest growing cities in the world. In addition to this the introduction of modern equipment, both equipment for water extraction and equipment employing water, has accelerated the depletion of traditional water resources in the farming areas of the country.

To make matters worse, cultivated areas have habitually been expanded as soon as any source of water has become available. This consequently entails high extraction, coupled often with careless and inefficient use.

This drastic change in water use is most marked in the central area of Saudi Arabia, where water is always in short supply. Most of the population live in wadis of the central area, and these mostly flow along the eastern slope of the 800 km long Tuwaig mountain.

To provide a clear example of water utilisation in these wadis, it was decided to select the Wadi Hanifah as a wadi typical of the region. Other considerations also favour this choice:

(i) The historical importance of the wadi since the establishment of the present Saud Royal family, whose capital was first Ad-Dir'iyyah and later the city of Riyadh.

(ii) The size of the wadi and consequently the age and size of the old villages and farming areas : the wadi is one of the largest of those flowing from the Tuwaig mountain.

(iii) Its closeness to the capital city : this has entailed the availability of, relatively speaking, a great deal of data and material, partly as a result of the interaction between the city and the wadi with regard to the water supply.

1.1 The Area of Study

The name of the Wadi Hanifah comes from the Bani Hanifah tribe who occupied the wadi two centuries before the rise of Islam, probably in 420 AD (Al-Jasir, 1966). Al-Erdh was the popular name for the wadi in the few scattered historical studies. This name, however, according to Yakout Al-Humawi (1955) used to be given to any wadi in Arabia where there was sufficient water for irrigation. The advantages of water and agriculture gave the wadi a particular importance in many historical events. One of these was the war of Apostasy near Al-Jubailah village, between the Bani Hanifah and the army of Kalif Abu Bakr a few years after the death of the Prophet Muhammed in the seventh century AD. Again, the wadi in the eighteenth century and afterwards was the leading political region in Nejd, and a large area was ruled from time to time from Ad-Dir'iyyah. Lately, since 1931, the bulk of the Arabian Peninsula has been united and ruled from the city of Riyadh.

The Wadi Hanifah drainage extends along the eastern flank of the Tuwaig mountain and lies between latitude 25° 00' and 24° 20' N, with an area of 4,053 sq km (Figure 1.1). At the crest of the escarpment it attains an elevation of about 900 m . above sea level and flows down the east-dipping sediments to join with one of the Wadi Hanifah's

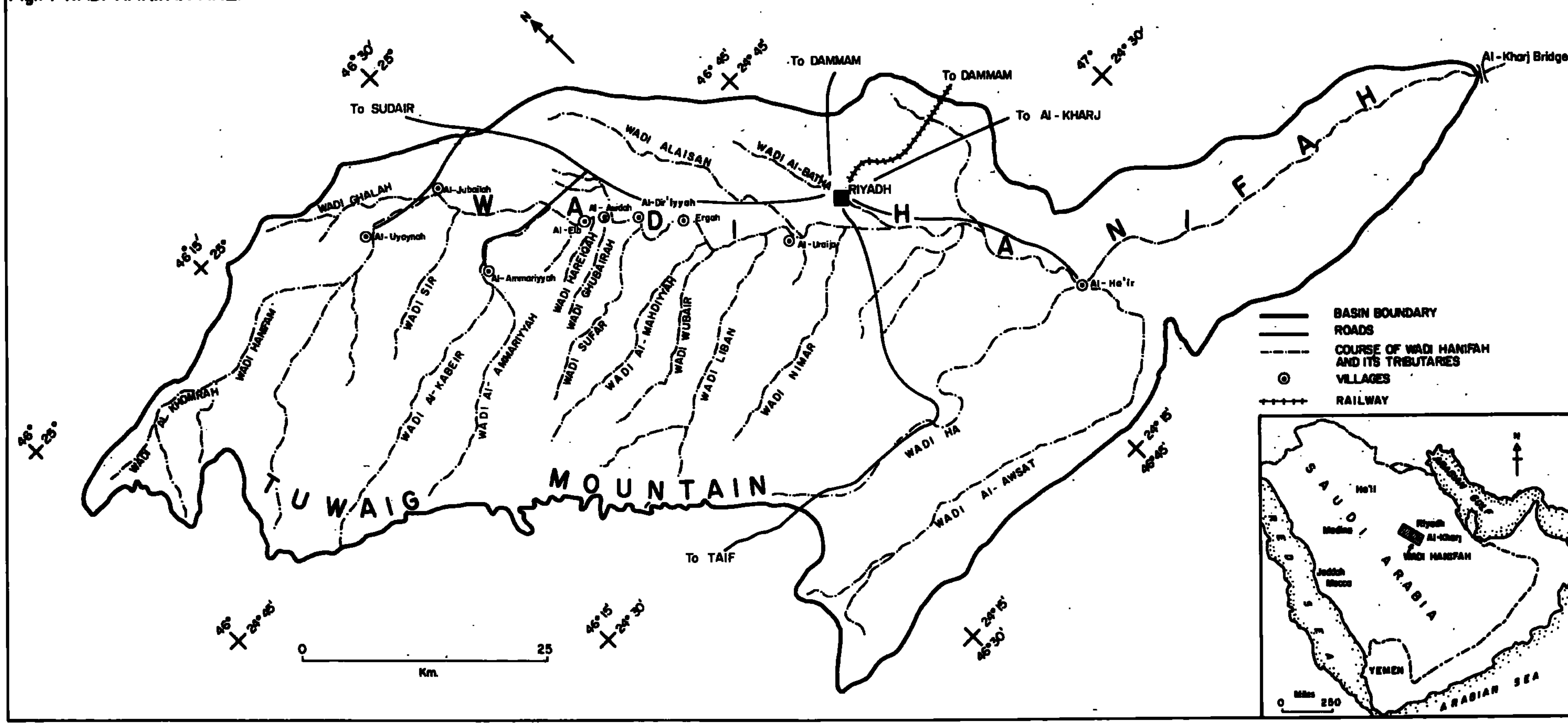


Fig.1·1 WADI HANIFAH AREA

main tributaries, the Wadi Al-Khomrah, which flows at right angles to the direction of the principal wadi. The wadi changes direction, following the outcrops, and striking towards the south-east, just after leaving Al-Jubailah village, where it is joined by a cluster of tributaries. Apart from the Wadi Alaisan, and the Wadi Al-Bat'ha, these follow the initial slope of Tuwaig mountain, as does, for example, the Wadi Al-Ammariyyah.

The cultivated areas and population centres are concentrated in a section of about 90 km between Al-Uyaynah in the north and Al-Ha'ir in the south. Here, the channel of the wadi, with an alluvium deposit of about 60 m depth, supplies water for the irrigation of the cultivated terraces. Since run-off is limited and uncertain, water was traditionally obtained by the pull-donkey method from the hand-dug wells.

In this section lies Riyadh, the capital city, with a population of about 350,000 inhabitants. Situated in the eastern part of the area, it is connected by four highways with the Taif in the west, the Sudair region to the north, Dammam to the east, and the Wadi Ad-Dawasir region to the south.

The remaining settlements are old villages sited on either bank of the wadi proper, except Al-Ammariyyah village which lies in the Wadi-Al-Ammariyyah tributary. The largest villages in size and population are Ad-Dir'iyyah, Al-Uyaynah, Al-Ha'ir and Al-Ammariyyah. Their populations range between 4,000 in the case of Ad-Dir'iyyah to about 1,000 in Al-Ammariyyah. The remaining villages of Al-Jubailah, Al-Awdah, Al-Elb, Al-Uraija, Ergah, Manfouhah and Al-Masan'i have populations ranging between 200 and 1,000. The estimated total population of all the villages is about 10,000. This means that about 97 per cent of the whole population of the region live in the city of Riyadh (Ministry of Labour and Social Affairs, 1964).

Through the period of water shortage which started roughly in the 1940's, the wadi region has witnessed major changes, largely due to the expansion of Riyadh city. Though the city appeared at first to be a market for the agricultural products and livestock of the wadi, the rising standard of living paved the way for a larger and more sophisticated and competitive market, and also for the absorption of the nomad population of the region.

Vegetation is limited by the amount of rainfall and the type of ecological environment. Since the bulk of the wadi basin consists of rocky limestone, particularly on the Tuwaig slope, and since rainfall is fluctuating and uncertain, the vegetation is found in wadi channels and in loamy micro-depressions.

The wild vegetation consists mainly of shrub and bush species, such as Calotropis procera, and in ephemeral annual species growing after rain and belonging to various families, for example graminaceae and plantaginaceae.

Although the ephemeral vegetation is the source of pastoralism in Arabia, in the Wadi Hanifah it is hardly used at all for grazing because of the diminution in nomadism. Instead, it is used to provide recreation for sightseers on excursions from the capital and nearby villages.

The wadi remains an important agricultural region in the central area, with a volume of produce dependent on the water available. The cultivated area, according to the census of the Ministry of Agriculture and Water (1964), is potentially 5,026 hectares. Nearly 65 % of this area is actually under cultivation (Table 1.1).

According to the previous report, the average agricultural holding is 39·98 decares. The size of the individual holding is controlled by various factors, such as the age of the farm, the density of population in the village nearby, the income of the owner, and above all the availability of water. Though the bulk of agriculture is sited in the wadi proper around the ancient villages - for example, Al-Uyaynah and Ad-Dir'iyyah - the isolated farming areas in the wadi seem to contain larger holdings. This is due to the fact that market gardening and the cultivation of alfalfa is commonly practised here whenever possible.

Palm groves have always played an important part in local agriculture. The total number of date palms was estimated at 252,662 in 1964. The palm grove holdings contain a few fruit trees such as oranges, citrus, pomegranates, apples and figs, and they occupy nearly 24 per cent of the area under cultivation. Vines grow outside the palm groves, particularly in the newly cultivated areas, for example at Al-Uyaynah. Traditionally they used to be near the water pool when the animal-pull method was used, and in some holdings they are planted in a corner of the palm groves.

Alfalfa is grown in palm groves and sometimes outside. It grows on loam and loamy sand in a total area of about 272 hectares. In addition to the local consumption, Riyadh city is the main market for the excess products.

Cereals, sorghum and millet are also commonly grown whenever water is available. The amount of land used for this in 1964 was in the order of 2,516·4 hectares. The land is irrigated in strips ranging bet-

TABLE 1.1

Agricultural Holdings and the Area under Cultivation in the Wadi Hanifah*

Location	Village	Number of Holdings	Area under Cultivation (decares)***	Average Area of Holding (decares)***
Wadi Hanifah proper (from north to south)	Al-Uyaynah	65	5,114	78·67
	Al-Jubailah	19	2,339	123·10
	Al-Mughaider**	9	1,147	127·44
	Al-Elb	13	771	59·31
	Al-Awdah	23	478	20·78
	Ad-Dir'iyyah	77	6,227	80·87
	Ergah	59	2,584	43·80
	Al-Ghithwanah	5	56	11·20
	Al-Batin**	14	1,379	98·50
	Al-Uraija	40	2,020	50·50
	Al-Badi'ah	22	1,547	70·32
	Manfouhah	48	1,737	36·19
	Al-Masan'i	46	1,834	39·87
	S'iah**	28	1,766	63·07
	Uraidh**	4	257	64·25
	Al-Mansouriyyah**	1	237	237·00
	Al-Ha'ir	152	1,640	10·79
Wadi Al-Ammariyyah	Al-Ammariyyah	26	1,891	72·73
	Abalkbash**	11	1,790	162·73
Wadi Alaisan	Um Al-Hamam	3	247	82·33
	Alaisan**	3	162	54·00
	Al-Ma'ther**	3	173	57·66
Wadi Liban	Liban**	8	407	50·87
Wadi Nimar	Nimar**	7	423	60·43
Wadi Ha	Dirab**	1	82	82·00
Total		816	32,627	39·98

* Agricultural holdings which have disappeared owing to the expansion of Riyadh City are exluded as a result of checking undertaken by the author in March 1974.

** Farming areas only.

*** A decare equals 1,000 sq m (or 0·1 hectare)

Source : Census of the Ministry of Agriculture and Water in 1964 ween 30 and 200 sq m, or in some cases these crops are grown between the date palms.

Market gardening has attracted reasonable attention in the last two decades. This arises mostly from the capital city being the nearest and the most highly absorptive market in the central area of Saudi Arabia. The area cultivated for these products amounted to 834·7 hectares. The main market crops are water melons, tomatoes, pumpkins, marrows, beans, melons, egg-plants, okra, cucumbers and peppers. Chief of all are water melons and tomatoes, which occupied respectively about 26 % and 14 % of the cultivated market gardening area. An expansion of the water melon plantations has been caused by the high demand of Riyadh during the hot summer.

It is, however, important to remember that, apart from the palm groves and orchards, the area under cultivation varies from year to year depending on the availability of irrigation water in the wadi alluvium aquifer. In a dry year, agriculture contracts and consists only of the cultivation of date palms and alfalfa. But whenever the aquifer holds a sufficient water reserve, cultivation expands to include the crops mentioned in the previous paragraphs.

The wadi seems likely to lose its agricultural status in the future through urbanisation and the related development trends now prevalent.

Bearing in mind that the substantial deep aquifer of Minjur is restricted to use for the urban supply within a fifty-kilometre radius of Riyadh, native farmers may give up their traditional farms and sell them to wealthy city residents, and in this way agricultural holdings could well be turned into beauty spots and recreational centres.

CHAPTER TWO

PREVIOUS STUDIES AND SCOPE OF PRESENT STUDY

2.1 Previous Studies

Being in an isolated area, the central part of Saudi Arabia, or "Nejd", had not been the subject of any major studies before the formation of Saudi Arabia in 1931. Such neglect by scholars resulted from the fact that this area is isolated by vast sand belts to the north, east and south, and by the Sarat mountains in the west. During the Ottoman Empire and the period of European expansion, this area had been left alone due to its harsh environment and to the poverty of its natural resources. Even when the Muslim Empire was expanding in North Africa and Central Asia, the Nejd area did not attract much attention in comparison with the Fertile Crescent in the north or the holy places in the west.

However, during the preparation of this study, it was found that the area has been referred to in one context or another through the years, and particularly in the last four decades. For the sake of convenience, the references will be classified as groups.

The old literature includes two groups - first, tribal poetry which gives some account of various aspects of the region, including descriptions of tribal areas when a poet is far away and homesickness makes him give a description of the tribal land, particularly the prominent features such as valleys, mountains, etc. From the people who used to live in the area during both the pre-Islamic period and the rise of Islam, came Al-A'asha, Jarier, Al-Farazdag, Thu Er-Rimmah, Al-Hutay'ah and others, whose verses are published and are available in the major libraries and bookshops of the Arab states. Because of the way of life at that time, when tribes moved from one place to another following the grazing area, no urban or rural knowledge can be gained; the only thing that can be detected is where they used to move, and the influence of the natural environment upon their lives. For instance, Amr Ibn Kalthoum, who lived before the rise of Islam, gave a very distinctive description of the west-facing cuesta of the Tuwaig mountain when he described it as "swords in warriors' hands". This picture, which describes the reflection of the sun's rays on the hanging wall of Tuwaig mountain, can be seen by travellers nowadays along the Riyadh-Taif highway in the area between Dhruma - 90 km west of Riyadh city - and Al-Washm - 80 km further westward.

The other group are the historians, either from the area or from the outside world. The history of the Wadi Hanifah as well as neighbouring areas is recorded by what can be called the Nejd historians. Chief of them are Husain Ibn Ghannan, who died in 1859 (1225 AH), Othman Ibn Bishr, who lived between 1795 (1210 AH) and 1873 (1290 AH), and more recently, Ibrahim Ibn Salih Ibn Eissa, who lived between 1853 (1270 AH) and 1924 (1343 AH). These three historians give the major political events after the movement of Sheikh Muhammed Ibn Abdul-Wahhab. Ibn Ghannam's record started about 1744 (1157 AH) and ended in 1797 (1212 AH), Ibn Bishr included the events mentioned by Ibn Ghannam and continued until the year 1851 (1268 AH). In addition, he mentioned older major events starting from the year 1446 (850 AH). Though these publications were devoted to local conflicts, mention of trade routes, prices, droughts and floods was not uncommon.

An even earlier period in the history of the Wadi Hanifah and its settlements is mentioned sporadically in some old literature devoted mainly to the sites of places and major topographical features. The most important book of all was "Mu'ajam Al-Buldan", written by Yagout Al-Humawey in the thirteenth century. In this book, the author concentrates upon the location of particular areas, and the tribes to which they belonged.

However, dealing with such literature requires a basic knowledge of the various historical names, and the existing names have mostly changed through the years. To give one example of the many wrong interpretations by present-day scholars, Abul-Ela (1965A) published a paper about some geographical aspects of the city of Riyadh in the Bulletin de la Societé de Géographie d'Egypt, in which he concluded that Yakout Al-Humawi does not mention Riyadh in his book. The fact is that, although the name Riyadh is not mentioned, the place does appear appropriately entered under its historical name of Hajr. The story of the invasion of the Wadi by the tribe of Bani Hanifah is also included. Thus, the existing names have to be converted to make sense of older historical literature.

In the nineteenth and early twentieth centuries, some European travellers reached the central part of Arabia. Palgrave (1865), Leachman (1914) and Philby (1922) were probably the only travellers to visit the Wadi Hanifah itself; although their publications are concerned with their personal observations, these explorers have the advantage of presenting their stories in an adventurous way. However, while their descriptions of villages, people and some social habits contributed new knowledge to outside readers, these covered phases of everyday life that were already familiar to native scholars.

Since the formation of the Kingdom of Saudi Arabia in 1931 and the adoption of Riyadh City as the capital of the new state, a period of detailed research has begun. The discovery of oil helped the state to send for scientific experts to launch new urban and rural developments. Being in the vicinity of the capital, which has grown fast during the past four decades, the Wadi Hanifah was the main focus of the search for a source of water to supply the city.

The first body to start investigation on the water conditions of the Wadi was the Arabian American Oil Company (Aramco) in 1947. Unfortunately, their report is not available, but other reports by the company dealt with conditions between 1938 and 1948, and included the work done by the company to evaluate the water level and provide a preliminary evaluation of the recharge of the alluvium aquifer based upon assumed hydrological conditions in the wadi.

A United States Geological Survey mission to Saudi Arabia, represented by Dr G F Brown, produced a report to the government in 1950 describing the main features of the geology and hydrology of the Riyadh Basin Area, and this assessment was used as a basis for various suggestions to solve the problem of lack of water at Riyadh. Their suggestions led to the drilling of test boreholes around Riyadh, and of one 60 kms to the east of the city. Though their approximate depths are about 230 m, the results were unsuccessful.

During the investigation by Dr Brown, International Bechtel Inc was carrying out a number of different contracts for the Public Works

Division, including a study of a new source of water for Riyadh. Their recommendations were given in two reports in 1951 : one concerned a subsurface dam at Al-Ha'ir, about 30 kms downstream from Riyadh; and the other involved a recommendation to drill a new well at Al-Ha'ir and pipe water to the city. The water level of the area around Riyadh and the nearby section of the Wadi Hanifah proper was measured during their investigation.

The Michael Baker Company submitted two reports as a result of their investigation in 1953. In a joint report written by George R Wilson of that company and Donald Doughtery of the US Geological Survey, they pointed out the economic disadvantages of building subsurface dams in the Wadi, as had been suggested previously by other firms. They also drew attention to the need for basic data concerning the rate of recharge and discharge of the alluvium aquifer. The company, which was in charge of drilling wells at Al-Ha'ir and constructing a pipeline and reservoir in Riyadh, submitted a report in June 1953, which reviewed previous suggestions by others, including the possibility of bringing water from Shat Al-Arab in Iraq.

Following the Michael Baker Company studies, sporadic studies were carried out by the Govenco Company and the Pakistan Technical Survey; both in 1954. Their work appears to have added little to what was already known. In 1954, the Hydraulique Afrique launched a study to find an additional water supply for Riyadh; during their work the deep Minjur Aquifer in the region was explored, preliminary drilling taking place west of Riyadh, at Ash-Shumaissi. Thus, a new source of water was discovered, but its aquifer conditions and quality needed a lot of investigation.

The Ralf M Parsons Company carried out a number of investigations in 1958 and 1959, including a study of the water level in the Wadi aquifer. Their work included an evaluation of water storage in the aquifer between Al-Uyaynah village in the upper section of the Wadi proper, downstream from Ergah village. Their studies were backed by new data and maps of the area under study, especially the report written by D L McCann, working under the technical direction of Mr R Davis, and assisted by members of the staff of the Water Resources Division of the Ministry of Agriculture and Water.

In 1959-60, Dr Wolfart, leading a German team, made an investigation into the neighbouring southern wadi, the Wadi Nisah. Though the area of the study is outside the Wadi Hanifah area, their work in the Fault Zones of the Wadi Nisah explained some of the geological aspects of the Wadi Al-Awsat, a feeder of the Wadi Hanifah in the Al-Ha'ir area, which used to be a tributary of the Wadi Nisah.

In the early 1960's, studies were carried out by G F Brown of the United States Geological Survey and C F Lough of the Ministry of Agriculture and Water of Saudi Arabia, on the existing water resources, mainly the Minjur Aquifer, Wadi Nisah and Dahl Heit. Their work was devoted mainly to the quality of the water in these resources.

The latest completed investigation was carried out by the Sogreah Company between 1966 and 1968. Their studies included the Wadi Hanifah, Sudair, Al-Washm, Al-Hautah and Al-Kharj, which constitute Area 5 according to the classification of the Ministry of Agriculture and Water. Various final reports were submitted in 1967 and 1968, including reports on ground water conditions, the agricultural and grazing potential; and a report about Riyadh Water Supply. Their investigation, which was carried out with new technical equipment, gave logical results concerning the present water conditions in the area.

In addition to these investigations, some official staff of the Departments of Geology and Hydrology in the Ministry of Agriculture and Water produced various papers and articles, some of them published and some confined to Ministry use. Most of these studies gave a general idea of water conditions in the whole or part of the country. The Department of Hydrology, which provided data on climate and on surface water, produced two reports about the Wadi Hanifah Dam.

2.2 The Scope of the Present Study

In starting work on this study, the major obstacles were to discover what kinds of investigations had been made, and where and how to find them. The rapid development and the movement of staff in the government offices consequent upon promotions or the expiry of work contracts made most of the material written previously difficult to trace.

Accordingly, two field trips were made : the first was carried out in August-September 1972 and involved exploration and enquiry. Visits were paid to different offices in the capital city, including the Ministry of Agriculture and Water, the Central Planning Organisation, the Municipal Affairs Office, the Ministry of Petroleum and Minerals, the Technical Co-operation Office, the General Department of Statistics and the Headquarters of the VBB Company in Riyadh. The difficulty in tracing old material stems from the fact that, though most people have heard of the Wadi Hanifah as such, few possess detailed knowledge of the region. Consequently, most interviews had to include some mention of the areas and places that go to make it up. By the end of the trip, the scope of material which was available had been established.

During the second field trip, which was made in the rainy season from December 1973 to March 1974, systematic trips were made through most of the main wadi and main tributaries. The primary purpose was to check directly some of the physiographical and land use aspects, and residents and farmers were interviewed in different settlements. In addition, some of the wadi's features were photographed, including flood sheets in different parts. Data and maps concerning climate, flood and underground water were obtained mainly from the Ministry of Agriculture and Water and the Ministry of Petroleum and Minerals, including the aerial photographs of the wadi drainage.

The present synthesis of existing reports is meant to cover the overall Basin of the Wadi Hanifah in terms of its main water resources. This task did not appear to be possible at first due to the fact that previous works had concentrated on finding sources for the Riyadh water supply, and had not studied the areas as a whole.

The physical background is dealt with in the chapters on Geology and Physiography. The former shows the different geological formation outcrops of the drainage basin and discusses their importance in terms of water bearing. The latter highlights the physical features of the wadi that influence the surface water runoff as well as the percolation processes. The surface water is tackled in the chapters on climate and runoff. Rainfall is obviously the only source of surface runoff; therefore concentrated attention is given to the climatic conditions in general and rainfall in particular. Run-off is studied in terms of flood occurrence, and an account is also given of the major features which influence it. With regard to underground water, which is the only source of water in the wadi, three chapters tackle the only three local aquifers separately. Each one contains, as far as possible, the condition boundaries of the aquifer, including the recharge and discharge and water quality, and the tapping development. In dealing with the Minjur Aquifer, which holds a deep fossil water, an expansion of the study was made to cover the general characteristics of the aquifer as a whole, with an emphasis on the depth, recharge, discharge and the water table in the study area. The reason for such expansion is that this aquifer is the present and foreseeable water resource for the urban sector in the wadi. Investigations are being carried out to tap this aquifer outside the wadi basin, and pipe the water to the capital city.

In the Conclusion, the present water condition is summed up as a whole, and the future outlook is considered. Although many points remain to be clarified when their basic data become available, a great effort has been made to give an accurate and correct picutre in this study, including the provision of accurate data, maps, names, locations, etc.

It is hoped that this study will be of great value in tackling the water problem not only of the Wadi Hanifah, but also in the whole central part of Saudi Arabia, and that it will contribute to the promotion of the geographical approach in the study of water resources in Saudi Arabi a.

CHAPTER THREE

GEOLOGY

A discussion of the geology of the Wadi Hanifah catchment almost inevitably necessitates some prior account of the major geological features of the Arabian Peninsula, and especially of the way the present structure of the sedimentary strata came into being. Before the 1930's, little was known about it, as a result of difficulties caused by political isolation, topography and climate. The creation of a modern political state in the Kingdom of Saudi Arabia led to the first investigations of the stratigraphy and structure of the sedimentary rocks when the Arabian American Oil Company (Aramco) started exploring for oil in the eastern province. In September 1933 two American geologists, R P Miller and S B Henry, arrived at Al-Jubail docks on the western coast of the Arabian Gulf and began their work for the California Arabian Standard Oil Company (Casco), the former name of Aramco (Lebkisher, 1965). From that date onwards, American geologists in particular have produced detailed studies of the geological sequence of Saudi Arabia. The two most outstanding, who have produced a great deal of work on the sedimentary section of the country, are Max Steinke and R A Brampkamp (1952). They arrived at the field in the autumns of 1934 and 1936 respectively. A major study was published by US Geological Survey (1958) and consisted of 21 maps, comprising geological and geographical information, and covering the entire area of Saudi Arabia. The maps have since been a basic tool for the geological and geographical study of the country.

The central part of the Arabian Peninsula, on which the Wadi Hanifah developed its catchment, consists of a deposition of marine and non-marine rocks standing on a vast mobile Pre-Cambrian complex of igneous and metamorphic rocks, which are exposed in the western part where they carry the name of the Sarat Mountains. Up to the Eozoic era, the Basement Complex formed part of the Gondwana continent, which extended from Australia to South America. To the north and east of Gondwanaland a long geosynclinal sea in the Tethyan Trough occupied an area covering Turkey, Iraq and the southern part of Iran. By the outset of the Paleozoic epoch, the surface of the Basement had been reduced to a nearly level plain (Powers et al, 1966). After the Devonian Age, the vast epicontinental seas, which were rich in marine life, moved back and forth across the lower part of the Basement. During this process their floors were filled by accumulated deposits which originated mainly from the hard calcareous part of the marine organisms and formed successions of almost flat-lying strata, semi-parallel to the Old Shield (Fisher, 1971). Destruction of the Tethyan Trough by orogenic movements started as early as the late Cretaceous period and continued until the beginning of the Cenozoic Age. In the late Tertiary, probably in the Miocene and Pliocene periods, the rocks of the Trough were folded and thrust up to form the mountains of Taurus and Zagros. Subsequently, the remaining part of Tethyes, the Mediterranean Sea, was separated from the deepest part of the trough which is now occupied by the Arabian Gulf. Additionally, the sedimentary strata of the Peninsula were tilted towards the east (Lees, 1928) and the Arabian Gulf also joined the Oman Gulf. As a result of the extensive tectonic framework, the Arabian Peninsula started to take its present shape. In the western part of the country, the Basement Complex was not affected by the uplift folding because of its high resistance. Instead, the great rift-fault system of the Red Sea and East Africa occurred during that period. At the outset of the Pliocene, the Red Sea was blocked out from the Tethyes seaway (the Mediterranean), and was connected with the Indian Ocean (Wilson, 1928).

However, our understanding of changes in the earth's skin, as they occurred both in the Arabian Peninsula and elsewhere, has recently been changed by the theory of Plate Tectonics put forward by H H Hess in 1960. A discussion of the elements of this theory is not relevant here, but the theory itself must be taken into account in any estimate of the future geological outlook of the area. If the theory is correct, then the geological development is still continuing. In other words, the folding action of the Zagros and Taurus Mountains is still active, which means, according to Flint and Skinner (1974), that the Arabian Gulf will disappear in the course of 50 million years, without any distinct change in the Red Sea, except that it may be connected again with the Mediterranean Sea through the Suez Canal.

The Arabian Peninsula has also been affected through the geological ages by deformation, faults, volcanic lavas and erosion. Within the sedimentary rocks, the effects have appeared as unconformities, disconformities in the contact of the sedimentary beds, and tensions in folding, producing domes, the latter located in the eastern province of the country. It is in these that the oil has been trapped.

Regarding the Wadi Hanifah Basin, it follows the geological order of the sedimentary section of central Arabia. The southern part of the basin also has been affected by the graben and fault system which extends as far as the Haradh area in the east and al-Artawiyyah in the west.

Apart from the grabens and faults which are physiographically clear, some of the geological units are locally disrupted, as is the Jubaila limestone, which is thrown down against the Tuwaiq limestone in the hanging-wall block of the Wadi Al-Awsat.

In general, the basin falls largely within the Tuwaiq Mountain, and the rocks were formed during the upper Jurassic and early Cretaceous periods.

The geological sequence of the outcrops consists of seven formations:-

(1) Tuwaig Mountain Limestone

(2) The Hanifah Formation

(3) Jubaila Limestone

(4) The Arab Formation

(5) Hith Anhydrite

(6) The Sulaiy Formation

(7) Quaternary Alluvium

as shown in Figure 3.1 and Table 3.1.

3.1 Tuwaig Mountain Limestone - Upper Jurassic

The name of the formation comes from Jabal Tuwaig, which extends from near latitude 17°30'N to 27°30'N : a distance of more than 1,200km. It forms the top ridge of the mountain and has a well-defined westward-facing cuesta shape. This formation is regarded as a good example of the more resistant sedimentary formations in Saudi

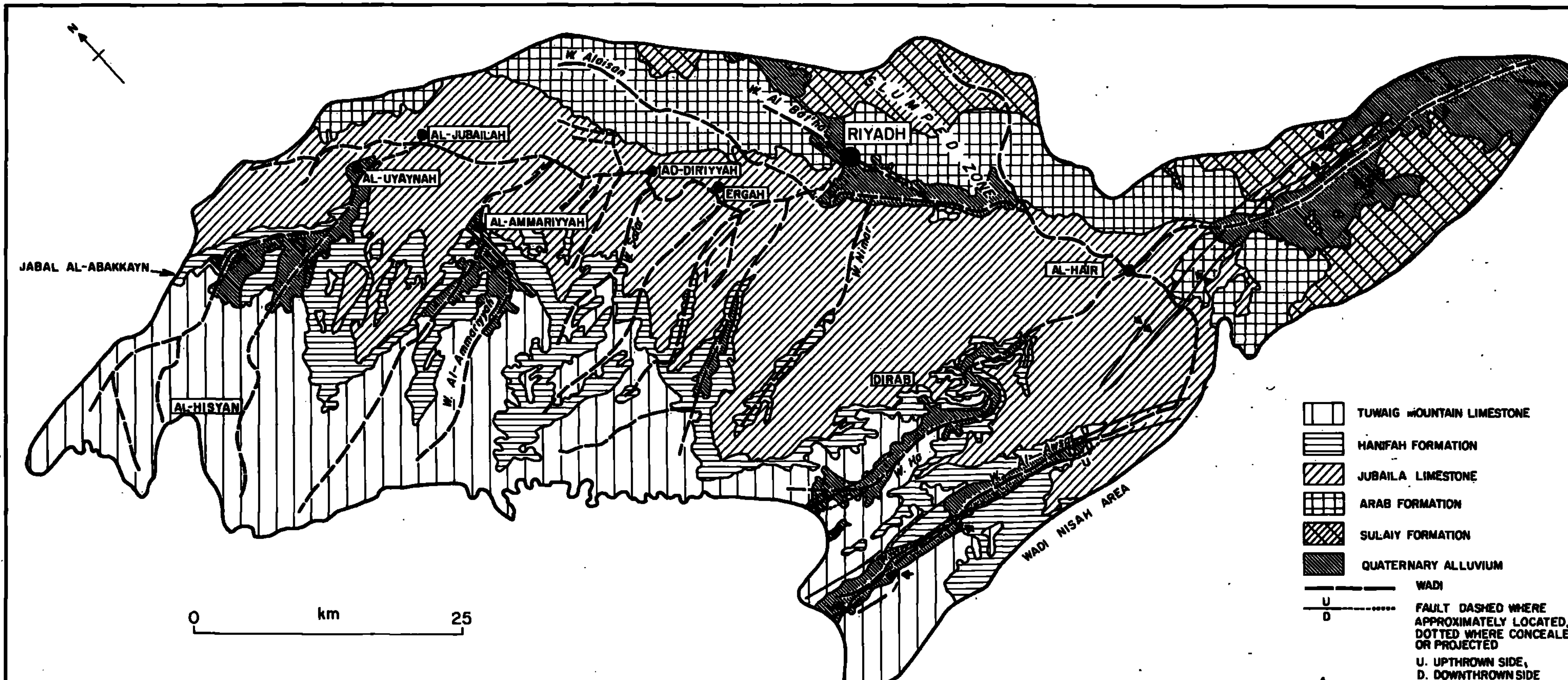


Fig 3·1 GEOLOGICAL FORMATIONS OF THE WADI HANIFAH BASIN
(Modified from U.S. Geological Survey Map I-207A, 1958)

TABLE 3.1
Wadi Hanifah Geological Outcrop Sequence

AGE		FORMATION	LITHOLOGY	THICKNESS (m) (Type or Reference Section)	GENERAL LITHOLOGIC DESCRIPTION
Quaternary		Surface Deposits			Gravel, sand and silt
Quaternary		Alluvium		60	Silt
Cretaceous	Valanginian / Berriasian	Sulaiy		170	Chalky limestone
Jurassic	Tithonian	Hith		90	Anhydrite
Jurassic	Tithonian	Arab		125	Calcarenite and aphanitic limestone, dolomite and some anhydrite. Solution-collapse carbonate breccia on outcrop
Jurassic	Kemmeridgian	Jubaila		±120	Limestone and dolomite
Jurassic	Kemmeridgian	Hanifah		120	Limestone and calcarenite limestone
Jurassic	Callovian / Oxfordian	Tuwaig Mountain		215	Limestone. Abundant corals and stromatoporoids in upper part

Arabia (Abul-Ela, 1965B). In the central part of Tuwaig, the difference of elevation between the escarpment and the plain in front is more than 500 m. At the south and north ends, the relative relief gradually decreases, and the limestone occurs as very low weathered benches. With the exception of the northern part, which loses its elevation gradually, the elevation of the Tuwaig mountain is about 1,000 m above mean sea level. Some 90 to 100 m of the formation can form almost vertical cliffs, for example those which can be examined at close quarters in Sha'ib Nisah, southward of the Wadi Hanifah. In addition, 30 to 40 m of argillaceous rock belonging to the Tuwaig mountain formation and subject to weathering lie below the vertical cliff, and appear to be an extension of the gentle slope established in the underlying Dhruma formation.

The upper part of the formation constitutes a strong plateau surface, sloping gradually eastwards to the slumped zone, particularly in the area under study. The surface of the slope is bevelled, and more recent beds dip downwards.

The vertical cliff is cut by a number of traverse channels, running from north to south. Three examples are to be found in the Wadi Hanifah region, i.e., Al-Hisyan in the north, and the Wadis Ha and Al-Awsat in the south. While the Wadis Al-Awsat and Ha were, on the one hand, the result of faults and grabens, the Hisyan, on the other hand, might have been caused by erosion reducing the vertical cliff to a step-like slope.

In the southern part of the Wadi Hanifah basin, the Tuwaig Mountain Limestone is present at Al-Awsat graben, as prominent edges and erosional remnants. Here, the lower beds - some 33 m - are relatively softer than the upper layers, and show conformity with the uppermost layers of the underlying Dhruma formation (Aramco, 1962).

The eastern slope of the Tuwaig mountain is ended by a wide valley separating the Hith Escarpment to the east from the mountain to the west, and in this the Wadi Hanifah channel is eroded.

The thickness of the Tuwaig limestone as a whole reaches a maximum in the southern part of the Wadi Hanifah area. Here, between the Riyadh-Taif Highway and the Nisah area (Lat. 24° 15' N), the thickness has been calculated to be between 200 and 215 m. In the Salboukh borehole No 3, to the east of Ad-Diriyyah village, where the formation is overlain by the Hanifah formation, the log of the well showed that the thickness of the formation ranges from 215 to 261 m (Ministry of Agriculture and Water, 1973). At the Ash-Shumaissi borehole in Riyadh city (Lat. 24° 36' 43" N, Long. 4° 40' 38" E) its thickness was 203 m (Table 3.2). In the northern part of the Hanifah region, the formation appears to be thinner. Powers et al, (1966) have pointed out that a section measured near Al-Ghat (Lat. 26° 02' N) had a thickness of 130 m.

The lithologic characteristics of the Tuwaig mountain limestone include a white and cream compact, fine-grained limestone, with some calcarenitic limestone and calcarenite. The limestone is dense, particularly in the upper layers, which form the main escarpment and the western slope. Few fossils were collected from it during a previous study by Aramco geologists. The lower part (25 to 20 m) consists of a

TABLE 3.2

The Lithologic Sequence of Tuwaig Mountain Limestone

At Ash-Shumaissi Borehole

	Thickness in metres
Aphanitic limestone, grey to tan, compact, slightly impure; thin bed of dark grey, poorly sorted, skeletal at base	4·9
Aphanitic limestone, light tan, moderately porous; Foraminifera common, rare grey to white chert	24·4
Calcarenitic limestone, tan, moderately porous, skeletal; thin bed of grey-tan, strongly cemented, fine-grained, skeletal calcarenite at base	6·1
Aphanitic limestone, tan, slightly impure, moderately porous; common 'birdseye' texture, rare white chert	9·1
Calcarenitic limestone, grey, partially re-crystallised, fine-grained, pellet-skeletal	5·5
Aphanitic limestone and calcarenite; complexly inter-bedded tan compact aphanitic limestone and grey fine-grained, well-cemented biogenic calcarenite; common chert	3·7
Aphanitic limestone, tan, compact; common 'birdseye' texture	4·9
Calcarenite, dominantly tan, fine- to medium-grained, well cemented, partially re-crystallised, pellet-skeletal; common interbeds of tan aphanitic and calcarenitic limestone	13·4
Aphanitic limestone, tan, compact, rarely pelleted; commonly mottled with 'birdseye' texture; rare thin beds of tan, fine- to medium-grained calcarenitic limestone. Thin bed of grey, fine- to medium-grained, weakly cemented calcarenite at base	33·5
Aphanitic limestone, tan to gray, compact, in part marly and impure, rarely particlly dolomitised; occasional thin beds of grey, compact pellet calcarenitic limestone. Interval becomes progressively more marly, impure and pelleted in the basal part	97·5
Total thickness of Tuwaig Mountain Limestone	203·0

Source : Powers et al (1966)

well-bedded, highly fossiliferous, soft, chalky limestone which forms an even talus slope at the foot of the cuesta.

The hydrological properties seem to be poor or non-existent in the area under study, though to the north, at Wadi Huraymila, and to the south, at Wadi Wasit in Al-Aflaj, an aquifer is reported by Sogreah (1968A) to be workable. There the surface is in a cracked and weathered condition to a depth of 20 to 40 m. However, percolation presumably occurs within the channels of the Wadis, where the water accumulates in large quantities and remains for some time after the rains, to flow down through the joints.

3.2 Hanifah Formation - Upper Jurassic

The Hanifah formation derives its name from the Wadi Hanifah, where the type section was first described. Writings related to the formation, dated prior to 1952, consider it as a member of the Tuwaig group. Subsequent studies have since established that it belongs to a different formation.

The outcrop of the Hanifah formation follows a narrow curving zone comparable with the zone of the outcrop of the Tuwaig mountain. The eroded channels of the Wadi Hanifah and its tributaries on the right bank, descending down the eastern slope of the Tuwaig mountain (for example, the upper Wadi proper, the Wadi Al-Ammariyyah and Wadi Nimar) have exposed a westward extension of the formation. Unlike the underlying formation, the outcrop of the Hanifah unit varies in width from one place to another: for example, near the Riyadh-Taif highway at Dirab the width does not exceed 2 km, whilst in an area to the west of Ad-Diriyyah village, the outcrop measures over 20km in width.

The underlying and overlying rocks, which are harder and more resistant, give the Hanifah unit more protection. Nevertheless, the formation in the Wadi Hanifah region has weathered to a long, shallow trough. Rocks outcrop to the east and the west of the trough in the shape of a low, irregular scarp, which appears to be steeper in the east. Moreover, some rounded outlines of the unit are scattered over the Tuwaig mountain limestone.

In spite of the gradual decrease in the thickness of the formation to the north and south, but outside the area under study, this unit has a constant thickness in the study area of about 116 m. The previous investigation carried out by Aramco (Report No G. 27, no date) claimed the thickness in the Wadi Nisah area to be about 180 m. This seems to be an overestimate. The most accurate study so far was done at Jabal A-Abakkayn in the extreme north of the Wadi Hanifah watershed. Here, the thickness of the formation is 113·3 m (Bowers et al, 1966). The recent drilling (1973) of the Salboukh wells has shown the thickness of Hanifah to be about 120 m (Ministry of Agriculture and Water, 1973).

The lithological characteristic of the Hanifah formation is that it is basically a carbonate unit. It consists mainly of a cream-coloured soft limestone, with minor interbedded marls and tan clay shales. Several brown calcarenite beds occur in the middle and upper layers of the formation. These can be traced without interruption over almost the enite length of the outcrop. Isolated coral reefs are present in the middle and upper portions also (US Geological Survey, 1958). Many thin brown oölite beds are preserved : these are apparently more resistant than the interbedded limestone. The fragments of the oölite are embedded in the weathered surface, giving the outcrop a brown colour, and this characteristic also makes it easy to distinguish the Hanifah unti from the overlying Jubaila limestone. The continuity of the formation is disturbed in the southern part of the Wadi Hanifah drainage area, where the Wadi Al-Awsat and Dhruma grabens slice through the Tuwaig mountain and offset the various Jurassic units.

The hydrological properties appear to be very poor, owing to the cracked and weathered condition of the upper portion of the chalky limestone. Al-Ammariyyah village is the only place in the basin where the formation yields a small quantity of water.

3.3 Jubaila Limestone - Upper Jurassic

The name of the formations derives from the village of Al-Jubailah, in the upper part of the Wadi Hanifah basin, where a thickness of 75 m of rocks forms a resistant dip slope which caps the Hanifah formation. These rocks have subsequently been found to form the lower portion of the unit. The upper series forms a steep eastward - tilted plateau, slightly bevelled on the surface.

The outcrop extends over a distance of 1,100 km from north to south, curving around the Central Arabian Arch. The surface exposure occupies more than 30% of the present watershed of the Wadi Hanifah. Within this area it has been cut into by a large number of tributaries in the right bank of the main valley.

The thickness of this formation varies from one place to another in the study area, in contrast to the other Jurassic units, which show a relatively constant thickness. In the Wadi Nisah, its thickness is about 130 m, and in the central part of the Hanifah region, the formation has a similar thickness (Table 3.3). McCann (1959) claimed the thickness in the Wadi Hanifah channel to be about 100 m - nevertheless, it is safer to say that the thickness in the region ranges from 110 to 130 m. This figure is derived from measurements at Jabal Al-Abakkayn in the extreme northern part of the Wadi Hanifah catchment area, where the formation is reducing in thickness. The formation has a thickness of about 72 m at Wadi Huraymila, 20km north of Jabal Al-Abakkayn.

The Jubaila limestone consists mainly of a cream-coloured, compact, thick-bedded limestone. In the Hanifah region the unit is composed of aphanitic and calcarenite limestone, with some beds of resistant calcarenite. The contact between this formation and the underlying and overlying units is conformable. The light colour of the bed of Jubaila limestone contrasts sharply with the brown-coloured, compact pellet-oölite calcarnite rocks at the top of the Hanifah formation. On the other hand, the contact with the overlying Arab formation is also obvious, since the upper portion of Jubaila limestone contains thin calcarenite with some relatively dense and quite resistant aphanitic limestone. These rocks have been weathered to small fragments.

Joints and solution channels in this formation ensure that rocks of the Jubaila series form a main workable aquifer in the area (cf Chapter 7, Jubaila Aquifer). Furthermore, it has been established that this upper portion of the Jubaila unit, along with the alluvium in the Wadi Hanifah, was once the main source of water to the shallow hand-dug wells in the capital city and its environs

TABLE 3.3

A Section of the Jubaila Limestone at Wadi Nisah, Showing Thickness and Lithologic Sequence

	Thickness in metres
4. Aphanitic and calcarenitic limestone (6·0 m thick)	
Aphanitic limestone, tan to yellow, tight, chippy-weathering, partially re-crystallised; single thin bed of grey, tight, skeletal calcarenitic limestone near middle	1·5
Calcarenitic limestone, tan to yellow, tight, chippy-weathering, skeletal; occasional thin layers of aphanitic limestone and beds of grey-brown, tightly cemented calcarenite near middle and at base	4·5
3. Calcarenite (7·0 m thick)	
Pellet-skeletal calcarenite, grey to golden-brown, tightly cemented, fine- to medium-grained, rarely sandy; thin bed of golden-brown, tightly cemented, partially dolomitised, coarse stromatoporoid carbonate near base	7 0
2. Calcarenitic limestone and calcarenite (20·5 m thick)	
Dolomite, dark reddish-brown, compact, finely crystalline	1·0
Limestone and calcarenite; complexly interbedded, off-white to reddish-brown, partially dolomitised, tight, fine- to medium-grained, pellet-skeletal calcarenitic limestone and cream-coloured to golden-brown, tightly cemented, partially re-crystallised, fine- to medium-grained pellet skeletal calcarenite	12·5
Calcarenitic limestone, cream to yellow, tight, partially dolomitised, fine- to medium-grained, pellet-skeletal; rare thin beds of aphanitic limestone, common scattered coarse-grained shell debris at various levels	7 0
1. Aphanitic limestone (84·4 m thick)	
Aphanitic and calcarenitic limestone, approximately equal amounts of complexly interbedded, cream-coloured to yellow, tight, commonly partially dolomitised, very rarely sandy aphanitic limestone and golden-brown, tight, fine- to medium-grained, partially dolomitised, pellet-skeletal calcarenitic limestone; occasional thin beds of tan, tightly cemented calcarenite and finely crystalline dolomite	22·0
Aphanitic limestone, cream-coloured to tan, chippy- to rubbly-weathering, tight, rarely chalky, commonly sandy; occasional thin beds of brown, pellet skeletal calcarenitic limestone and tightly cemented calcarenite	62·8
Total thickness of Jubaila Limestone	118·3

Source : Powers _et al_ (1966)

before the vast expansion during the last few decades.

Wadi Hanifah cuts its channel through a long stretch of the Jubaila formation. The contact between the upper limestone and the alluvium is continuous along the channel from the Al-Ha'ir area as far as the area beyond Al-Jubailah village, and this upper portion of the limestone receives a small quantity of water through the alluvium and along the joints. Only in a small area immediately downstream of Ergah village is the non-bearing water series raised to the surface by folding. Though the tributaries in the right bank of the Wadi Hanifah intersect the Jubaila unit, the contact between the alluvium of these tributaries and the limestone occurs in the non-water-bearing rocks, except in the cases of the Wadis Ha and Al-Buaija in the southern sub-drainage area.

3.4 Arab Formation - Upper Jurassic

Until 1958, the Arab formation was classified as a member of the Riyadh Group, which contained Lower Riyadh and Hith Anhydrite. After 1958, the classification "Riyadh Group" was dropped, and the two formations were classified individually.

The Arab Formation occupies the eastern part of the Wadi Hanifah drainage area. In contradistinction from the exposure of the previous unit, the Arab Formation is characterised by the presence of several series of rolling hills, occupying a very badly slumped zone over the whole formation of the outcrop. These hills are separated and conical in form. In this section of the basin, the tributaries of the Wadis Alaisan and Al-Bat'ha cut their channel between those separated hills. Their flow is smooth, in unpronounced channels.

Slumping in the Arab formation could be accounted for by the theory that the anhydrite beds of Hith formation may have been dissolved beneath the overlying unit; the consequent extensive loss of material causing the slumping condition. Because the outcrop of the Arab formation is so badly affected, it seems to be more or less impossible to study a locality-type section in the Wadi Hanifah area. Thus the thickness of the unit and the lithologic sequence have not been accurately defined, although an attempt was made by Aramco in their sections on the Al-Kharj plain and in the Wadi Nisah. It has been reported that the rocks which could be measured were about 20 m in thickness (Aramco, Report No G. 27, no date). The upper beds of these sections were badly brecciated or slumped.

With regard to the thickness of the Arab formation and its lithologic characteristic, it is reasonable to follow the suggestions of Powers et al (1966), that the oil wells in the Eastern Province of Saudi Arabia are the best section in which to study the Arab unit.

At the outcrop in the area of the Wadi Hanifah, the basal carbonate rocks are small in quantity and the interior is mainly soluble Anhydrite. The composition of the other rocks is hardly known, owing to the effect of the solution collapse.

The contact between the Arab unit and overlying Hith Anydrite can be observed on the Dahl Heit (Lat. 24° 29' 8" N, Long. 47° 0' 6" E). The contact there between the Anydrite and the upper member of the Arab formation is conformable. Apart from this, the dissolving of the gypsum beds in the Arab formation at the outcrop has caused an admixture of the rocks of the Arab unit, with Hith Anhydrite and (probably) the Sulaiy formation.

Existence of ground water in the Arab formation had been confused in early investigations. The more recent study of Sogreah (1968A) and the Ministry of Agriculture confirmed that the aquifer might yield a small amount of water in a few wells east of Riyadh where the formation was cracked and weathered. However, water in the series is probably contaminated due to its existence beneath the city.

3.5 Hith Anhydrite - Upper Jurassic

An apparently complete Hith sequence is clearly visible in the sharp cliffed cave of the Dahl Heit, some 32 km south-east of Riyadh City. In the area of the Wadi Hanifah, where the Anhydrite might well have outcropped, there is no trace of it. The reason is that the area inside and outside the Wadi drainage, on which the unit could have outcropped, is a rather broad zone of badly slumped beds extending even beyond the Sulaiy formation (Upper Cretaceous). This phenomenon is attributed to the dissolving of Anhydrite beds within the underlying Arab formation. The extent of the slumped zone confirms the long period and great circulation of water, which has probably removed almost all the Anhydrite in the zone.

The first measurement of the Anhydrite was carried out by R A Bramkamp and T C Berger in 1938. The results showed that the thickness of the unit was 72·2 m, where the top of the Anydrite is in contact with some layers thought to be fragmental limestone (Powers, et al, 1966). The layers on top of these are collapsed breccia, which occurs with the loss of thick interbeds of Anhydrite. They bring the total thickness of the formation to 90·3 m (Powers et al, 1966).

The formation observed and measured at the exposure of Dahl Heit is composed mostly of light, blue-grey massive Anhydrite in the upper part. In the lower part, the Anydrite is interbedded with aphanitic limestone.

In addition to the type locality at the Dahl Heit, it was reported by Brown (1949) that the Anhydrite of Hith unit was found near Ain Ad-Dhil'a at Al-Kharj plain. This indicates that the formation does, in fact, extend south of the locality section. Through the vertical cliff of the cave of Dahl Heit, the Anhydrite is speckled with spherical and ovoid masses of gypsum, which probably originated from enclosed moisture at the time of deposition.

The massive Anhydrite is primarily impermeable to ground water. However, it is more soluble than the limestone, and, accordingly, whenever unsaturated water comes against it, caverns are formed.

3.6 Sulaiy Formation - Upper Jurassic and Lower Cretaceous

The name of this formation comes from the Wadi As-Sulay, which cuts its course at the foot of the Al-Aramah and Heit Escarpments. The outcrop is exposed in a north-south belt, covering a distance of more than 350km. The exposure of the Sulaiy unit is seen mainly in the lower part of the Wadi Hanifah. In some parts of the outcrop, within the Hanifah drainage, its rock is found in small isolated islands surrounded by Quaternary fills.

An accurate measurement of the total thickness of the Sulaiy unit in the locality section appears to be virtually impossible. The reason is that the formation at the outcrop is badly slumped, owing to solution of the anhydrite and limestone. Two attempts to measure the unit have been carried out by Aramco (Report No G. 27, no date) at Al-Kharj plain and its surrounding areas. A thickness of 9·7 m has been detected, fully exposed, at a spot close to Khafs Dighrah - a ground water pit. The other section was recorded in the northern part of the Wadi Nisah. Here a total thickness of 45 m of the upper beds is exposed. It goes without saying that the best known spot of the unit exposure is at Dahl Heit, where the basal beds are clearly visible. The most accurate measurement so far has been reported by Powers et al (1966) on the type section in the sharp walled cliff of Dahl Heit, where the total thickness of the formation is found to be about 170 m.

Throughout the Sulaiy formation, the main rock type is cream and tan, chalky compact aphanatic limestone, including a few thin oölithic beds. In the lower part, much interbedded calcarenite limestone, calcarenite and some breccia are present.

The age of the Sulaiy unit is not yet clear. While US Geological Survey (1958) had suggested that the Sulaiy could be of Neocomian age (Lower Cretaceous), Powers et al (1966) pointed out that it must date from the late Jurassic or earliest Cretaceous, i.e., somewhere between the Tithonian and early Volaginian.

In terms of ground water, the formation within the Wadi Hanifah basin appears to be very poor. Water has been traced only at some places outside the area under study, for example at the Al-Kharj plain and the Wadi As-Sulay (Sogreah, 1967).

3.7 Quaternary Alluvium

Wadi Hanifah drains its course through the resistant Jurassic units where the slope dips gently towards the east. It then flows in a north-west to south-east direction along the strike of the Jubaila formation. Beyond Al-Ha'ir village, the Wadi dissects the Sulaiy formation in a smooth, slow, wide channel, ending at the Al-Kharj plain. The general orientation of the Wadi after leaving the Tuwaig eastern slope is actually along a relatively wide trough between the dip-slope of Tuwaig and the Al-Aramah and Heit escarpments.

The Quaternary deposition in this long trough consists mainly of three major deposits:-

(i) Alluvium fill of wadi channels;

(ii) Wind-blown and alluvial silt, in undrained depressions;

(iii) Belts of drifting sand.

However, because the bulk of the Wadi Hanifah drainage area falls within the area of the Jurassic formations, which in turn are more resistant and steeper than the rest of the trough, the deposit in the channels of the Wadi and its tributaries are mostly of alluvium fill, controlled in their origin and extent by the structure of the underlying Jurassic series. Whilst drifting, as exemplified by small dunes of sand, is common in the trough, this is hardly found in the watershed.

Thus, the weathering process is mainly deflation. The contents of the deposits are either carried out by the water current, or laid down in the locality of deposit or nearby.

The distribution of the Quaternary fill occurs mainly over the upper part of Wadi Hanifah proper and the major feeders in the right bank, namely the Wadis Al-Ammariyyah, Al-Awsat and Ha. It is in this area that channels cut through the outcrop of the Hanifah formation. As the rocks of this formation are less resistant than the overlying Tuwaig and underlying Jubaila limestone, the wadis have eroded rather wide channels, with gentle slopes. The channels in this area are floored with an extensive layer of unconsolidated surface deposits of silt, sand and gravel, derived from the surrounding areas. US Geological Survey (1958) claimed that the sediment in this area may contain some unrecognised equivalent of other units of the Quaternary system.

In the middle part of the Wadi Hanifah proper, the Quaternary fill is controlled also by the surrounding geological units. A channel of about 60 m in depth, filled with sand, silt and gravel, is cut in the Jubaila limestone, extending from the village of Al-Jubailah downstream, as far as the Al-Ha'ir area. In this area the alluvium has been the traditional source of water for the Wadi Hanifah (cf Chapter 7, The Alluvium Aquifer).

The alluvium deposits consist of four different units of the Quaternary system, as shown in Figure 3.2.

(i) A silt terrace stands above the existing wadi survace. Here the terrace is the principal land available for cultivation and farming in the Wadi Hanifah region. Whole villages of the wadi are built on top of the channel cliff, adjacent to the silt terrace. A flood-water course flows in the middle and is separated from the terrace by man-

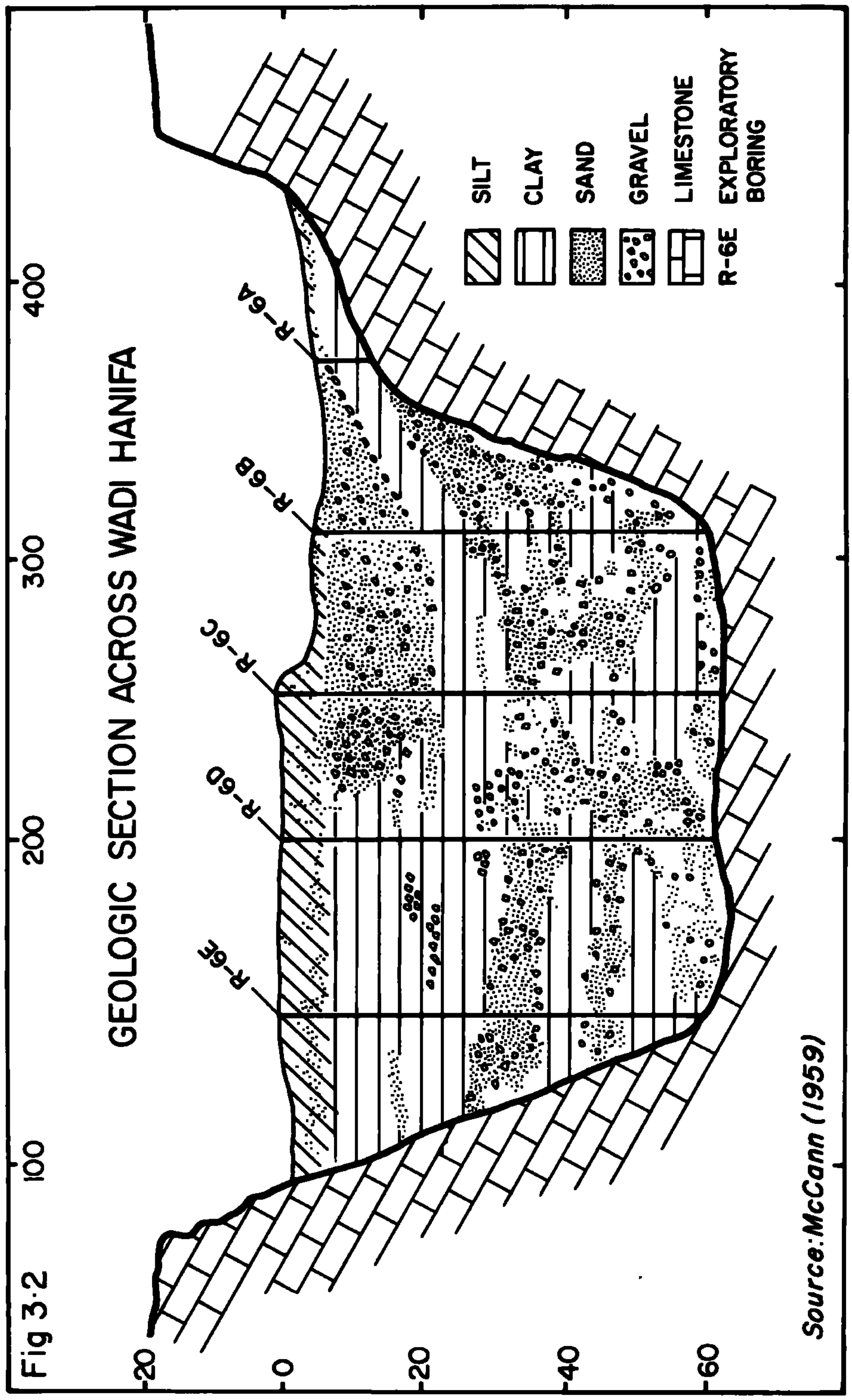


Fig 3·2
GEOLOGIC SECTION ACROSS WADI HANIFA
R-6A
R-6B
R-6C
R-6D
R-6E
SILT
CLAY
SAND
GRAVEL
LIMESTONE
R-6E EXPLORATORY BORING
100
200
300
400
CHANNEL WIDTH IN METRES
20
0
20
40
60
DEPTH IN METRES
Source: McCann (1959)

made walls to prevent further erosive action.

(ii) A former back-filled channel, containing sands and gravels. These sands and gravels consist mainly of calcareous materials, derived from weathered limestone.

(iii) Silt and clay; some gravel lenses are present.

(iv) Gravel clasts, ranging in size from granules to pebbles, and more frequently sub-rounded. There are also some Eolian sands, predominantly quartz, and clay lenses. At the base of the alluvium, a thin layer of dark grey, shaley material is found.

The alluvium in general within this section is unconsolidated. However, minor zones of caliche and gravel lenses, well cemented with calcium carbonate, are occasionally to be seen.

In the southern sub-catchment area, where the Wadis Al-Awsat and Ha cut their channels, a deposit of quartz, sand and limestone boulders is present at the base of the channel (Wolfart, 1961).

In the lower part of the Wadi Hanifah, downstream of the Al-Ha'ir area, where the channel widens and falls less steeply, the fill consists mainly of silt and associated fine sediment.

CHAPTER FOUR

PHYSIOGRAPHY

4.1 General Landform

The topography and the extent of the Wadi Hanifah Drainage has been influenced by the Tuwaig Mountain. Here, where the wadi has developed, the mountain stands as a resistant ridge in central Arabia.

Weathering processes, particularly weathering by water, have sculptured the western slope of the mountain, and it has come to form a vertical cliff rising about 120 m above the adjoining Dhruma plain to a height of more than 900 m above sea level.

The gradual eastern slope of the mountain, which is comparable to the sedimentary layers of Arabia, has been reduced in such a way that near the vertical cliff edge there is a nearly smooth stretch, devoid of protuberances, that dips slightly for about 300 m (personal observation).

Below the former point, various finger-tips of tributaries start to form incised canyons which become larger and deeper in the area where the formations of Hanifah and Jubaila outcrop, due to their softer beds. At the outcrop of the Hanifah formation, in particular, pydomical Jebals and many facet-like slopes have emerged.

At the central part of the wadi catchment, where the Jubaila limestone outcrops, the slope dips eastward by about 1°, but steeper angles can be locally distinguished resulting from collapse in the limestone (Sogreah, 1967).

In the extreme east of the basin region, a slumped zone begins on a small scale, its features gradually becoming more common further to the east. Most of the hills are conical, though some of early Cretaceous and Jurassic limestone are found (Abul-Ela, 1965B). The surface water in the slumped zone runs towards the south as a result of the collapse of the topographical forms.

However, apart from the slumped zone, the general slope appears to follow the initial slope of the Tuwaig Mountain and the overlying strata striking towards the east, and in some places towards the south-east (Fig 4.1).

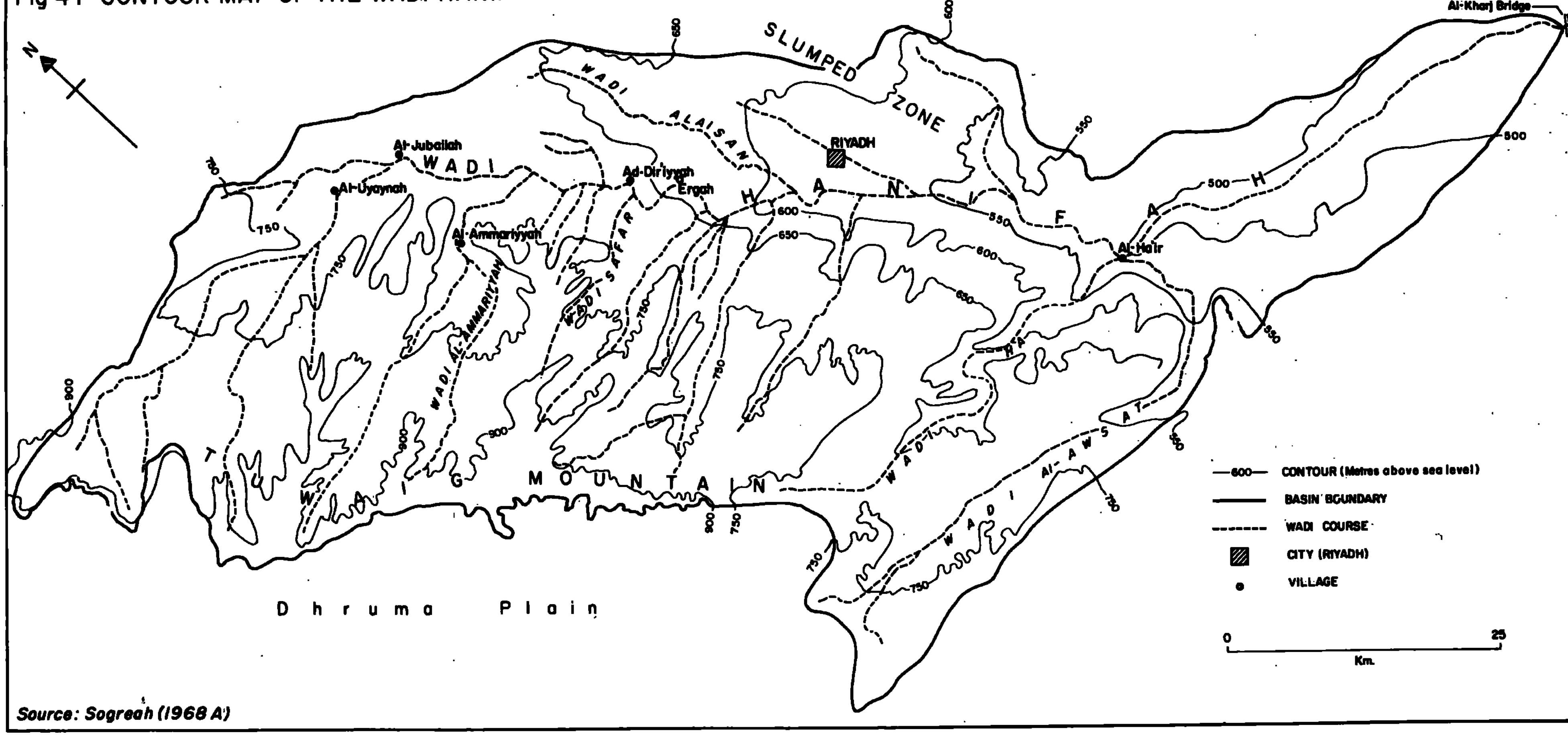
4.2 The Drainage Network

The Wadi Hanifah drainage basin extends between the eastern flank of the Tuwaig mountain in the west and the Aramah escarpment in the east, covering a pear-shaped catchment area of 4,053 sq km between latitude 25°00' and 24°20'.

The wadi rises near the crest of the east-dipping Tuwaig escarpment at an elevation of about 900 m above sea level, then flows down the dip slope of the Jurassic limestone (Tuwaig, Hanifah, Jubaila and Arab formations) in an easterly direction. In the vicinity of Al-Jubailah village, the wadi curves its bed along the successive outcrops in an approximately north-west - south-east direction (Sogreah, 1967), passing the capital city of Riyadh and then eventually flowing into the Al-Kharj plain and joining the great Wadi Sahba valley, which runs from west to east.

The direct length of the wadi is about 180 km (Fig 4.2). The bottom width is variable along the wadi. Leachman (1914) reported that the width of the upper part, near al-Hisyan, was about 750 m. Downstream, where the wadi is clearly marked by two cliffed banks, it

Fig 4·1 CONTOUR MAP OF THE WADI HANIFAH BASIN



Source: Sogreah (1968 A)

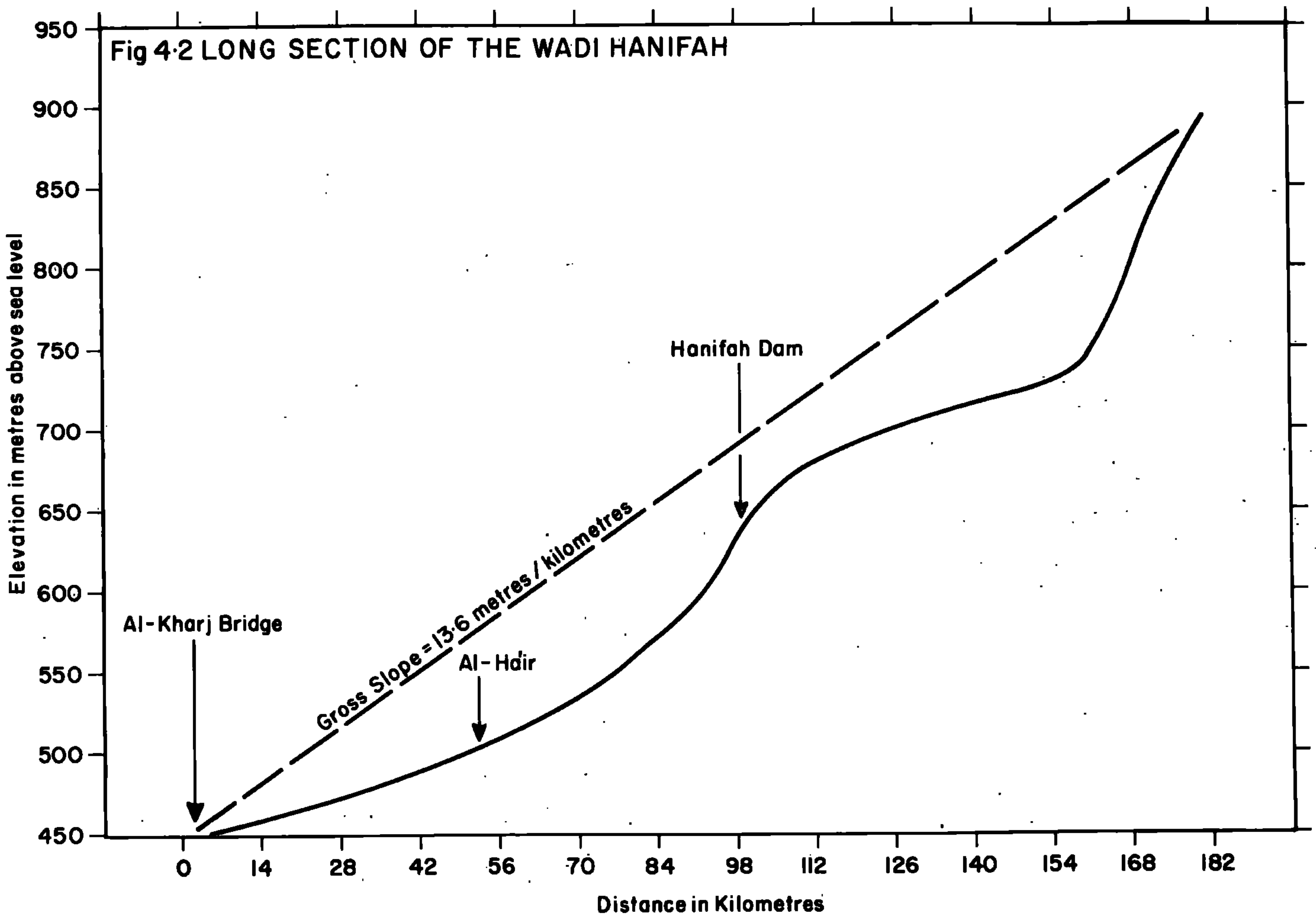


Fig 4·2 LONG SECTION OF THE WADI HANIFAH
Elevation in metres above sea level
950
900
850
800
750
700
650
600
550
500
450
0
14
28
42
56
70
84
98
112
126
140
154
168
182
Distance in Kilometres
Al-Kharj Bridge
Gross Slope = 13·6 metres / kilometres
Al-Hair
Hanifah Dam

reaches about 400 m (Fig 4.3). Between Riaydh City and the Al-Ha'ir area, the width ranges between 300 and 400 m.

The effective drainage area is from Al-Jubailah village to Al-Ha'ir along almost 90km of the wadi. In this area, where the wadi runs parallel to the Tuwaig escarpment, its right bank is joined by tributaries of varying length and size. On the left bank, two wadis feed the main valley, rising from the hilly outcrop of the Arab formation; the Wadi Alaisan, with a total length of 30km, unites with the main wadi in the Al-Ma'ther to the north of Riyadh, and the Wadi Al-Bat'ha , which has been affected by the expansion of Riyadh City, joins the main wadi to the south of the city. The authorities plan to include this wadi, utilised within the city, in the sewage system.

The Wadi Hanifah drainage can be sub-divided into four sub-catchment areas for the purpose of discussion (Fig 4.4).

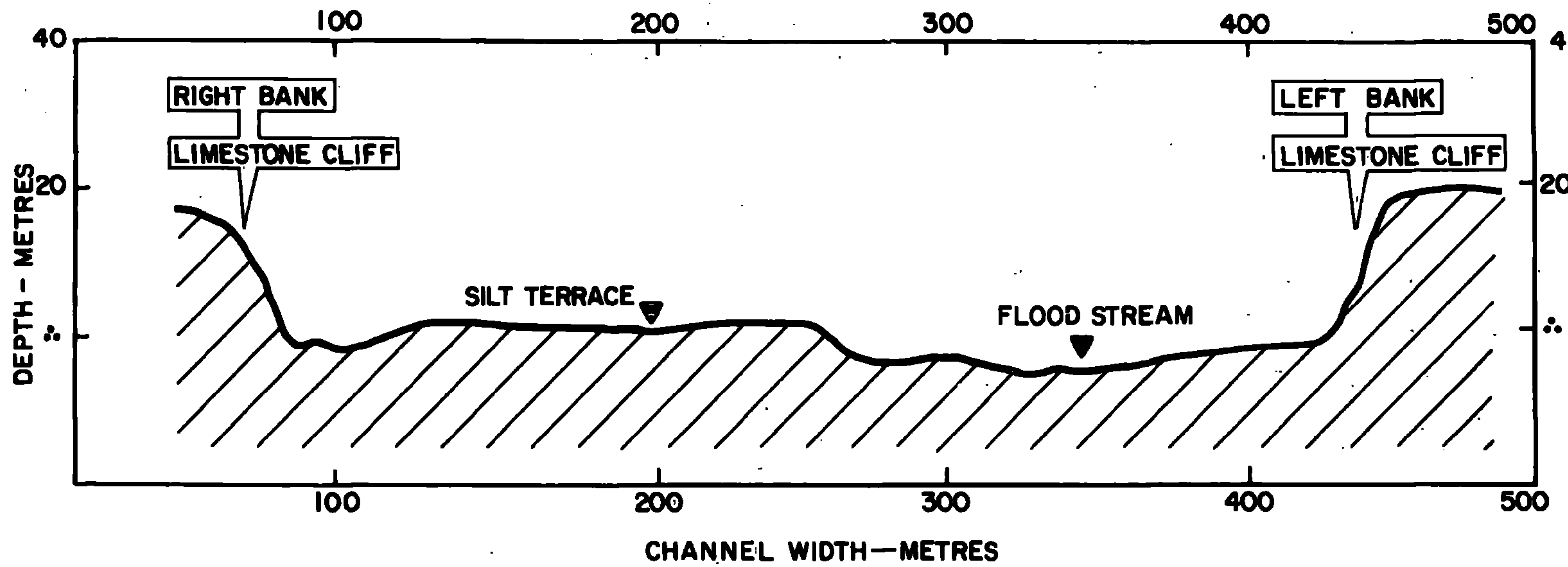
(i) Upper Wadi Hanifah Drainage

This area is bounded by the Tuwaig Crest in the west, and the water-parting which divides the Wadi Hanifah and the Wadi Salboukh-Sudous in the north. Two major small wadi groups rise at almost the same level and meet 20km west of Al-Uyaynah village, the Boudhah group joining the right bank and the Al-Ahaisi group the left bank. Al-Uyaynah and Al-Jubailah are two settled areas where the wadi channel has a layer of silt deposits and water is available from underground.

(ii) Ad-Dir'iyyah Drainage

This consists of a number of tributaries following the dip-slope of the mountain, and joining the main wadi at a rather sharp angle.

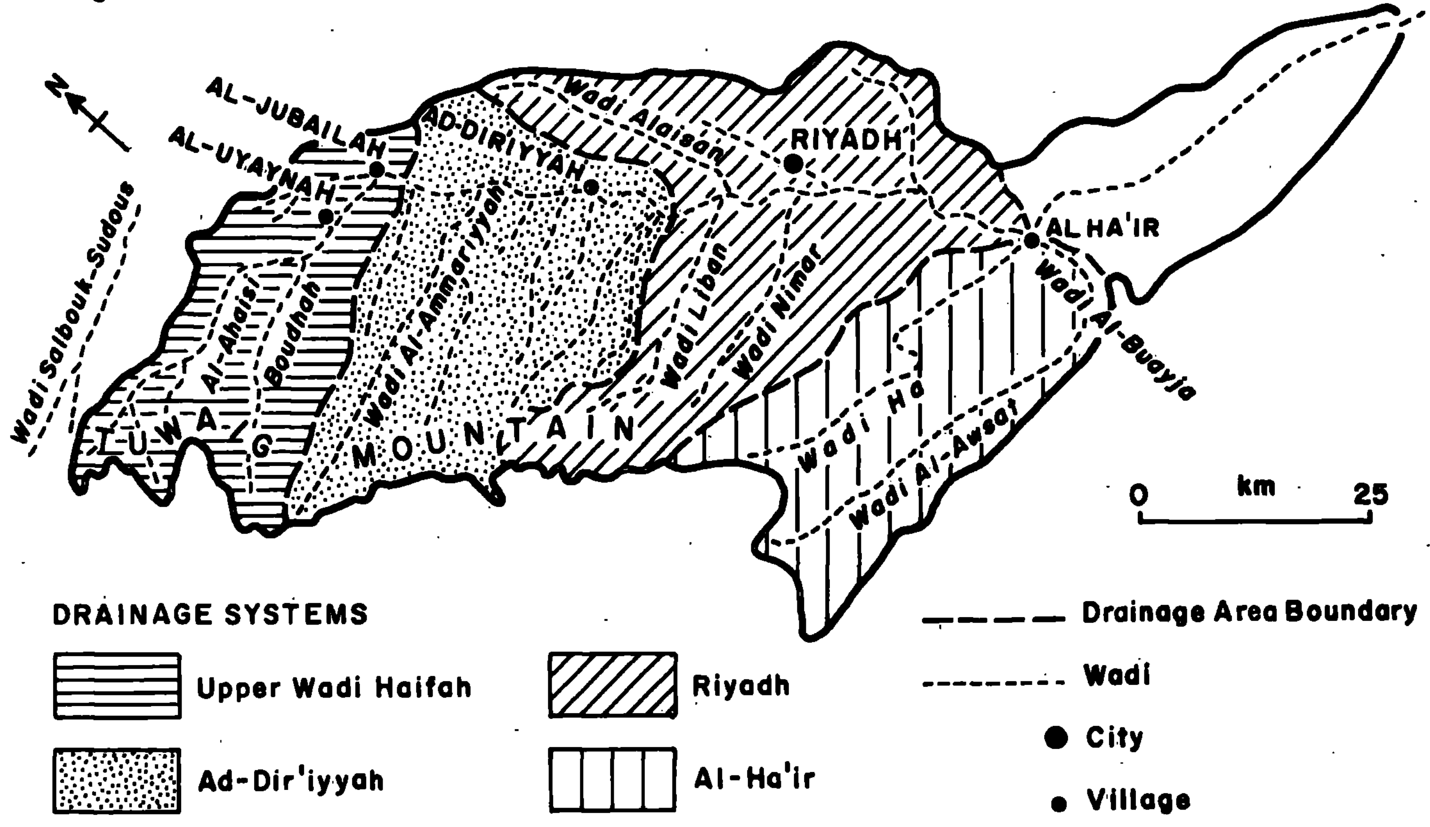
Fig. 4·3 CROSS SECTION OF THE WADI HANIFAH



Location: 1·6 Kilometres Downstream of Wadi Wubair

Source: McCann 1959 with some modification

Fig 4.4 WADI HANIFAH DRAINAGE NETWORK



They are in consequence characterised by deep channels and short runs. Ad-Dir'iyyah area is the most densely populated area in the wadi, apart from Riyadh City. The alluvial terraces make it possible to find an accessible water supply and suitable land for cultivation and settlement. However, the Ministry of Agriculture and Water has constructed four small dams on the main tributaries, besides the Wadi Hanifah Dam, to help in recharging the alluvium aquifer.

(iii) Riyadh Drainage

Here, the topographical features are slightly different, particularly in the left bank area by virtue of some scattered hills stretching along to the Arab formation. Thus the Wadis Al-Bat'ha and Alaisan join the Wadi Hanifah in the vicinity of Riyadh. On the Wadis Nimar and Liban, small impounding dams have been constructed to replenish the wells which help to supply the capital city.

(iv) Al-Ha'ir Drainage

In this area, the Wadi Hanifah is joined from the right by the Wadi Ha, which enriches Jebal Tuwaig within a graben, and the Wadi Buayja flowing from the east and south respectively. Advantage was taken of the junction of these wadis and the alluvial watersheds for the installation of a long complex of extraction works, comprising private wells and the Riyadh City wells. The ground water in this area is mainly stabilised by floods (Sogreah, 1967). The Wadi Hanifah leaves Al-Ha'ir in an easterly and south-easterly direction. The drainage downstream is comparatively narrow, and the course rather unpronounced.

4.3 Evolution of Drainage Network

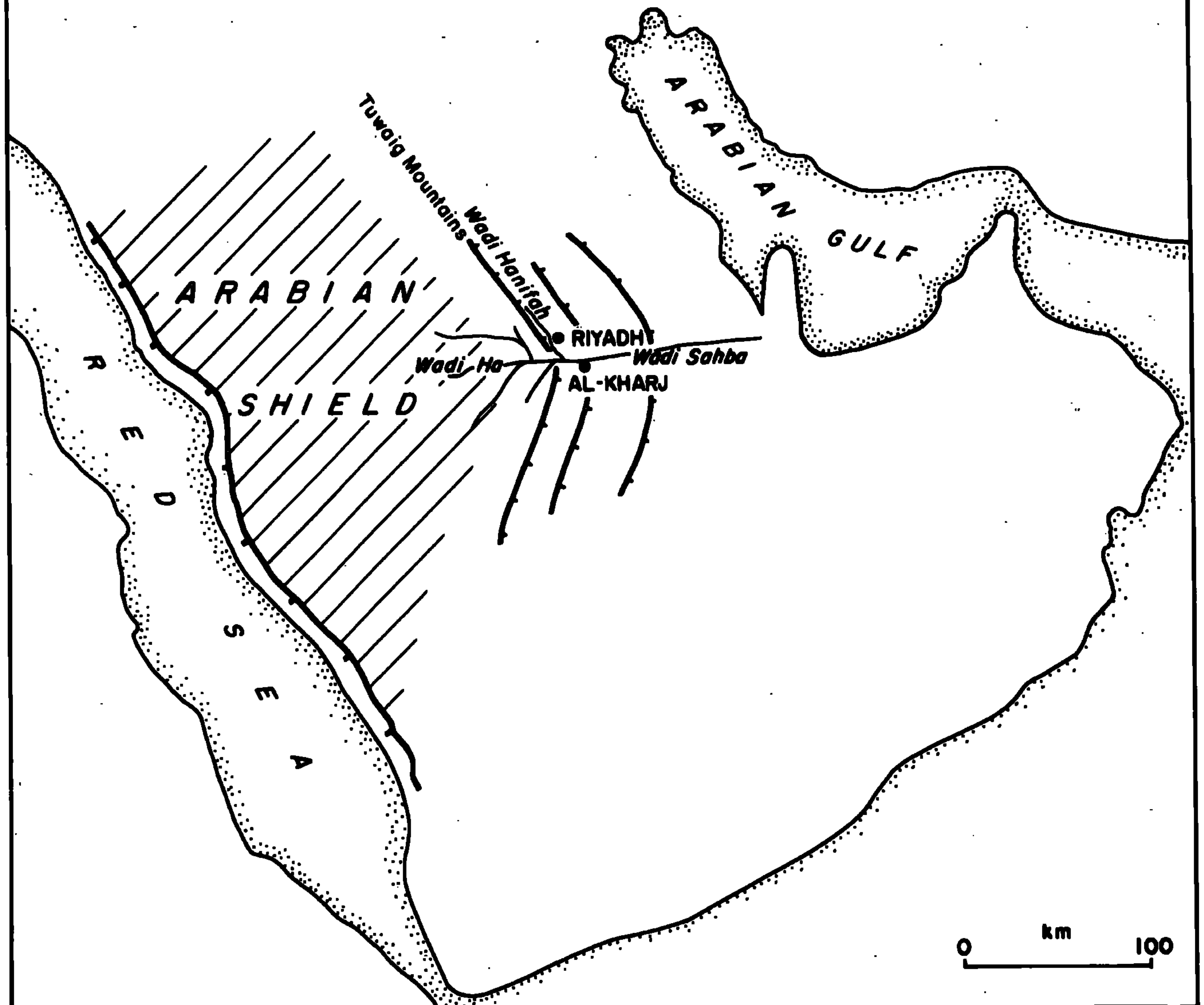
Since the Jabal Tuwaig slopes gently towards the east, a number of drainage systems have been developed following this general slope. Between them lie eroded plateaux and the drainage systems are separated by water-partings. These systems form a base for the replenishment of the shallow aquifers, and the aquifers in their turn made early settlement possible.

Within these drainage systems the Wadi Hanifah collects various tributaries along a stretch of nearly 70km between the Wadi Nisah in the south and the Wadi Salboukh in the north.

The present relief of the Hanifah drainage basin, particularly in the Al-Ha'ir drainage, developed after a gentle uplift that probably occurred in the Miocene or Pliocene eras (Wolfart, 1961). During and after the alpine epirogeny, the Wadi Ha - which at present belongs to the Wadi Hanifah drainage basin - drained the Dhuruma, Al-Muzahimeyyah and Al-Quway'iyyah regions, which are parts of the area covered by rocks of the Basement Complex (Sogreah, 1967). The Wadi Hanifah of that time flowed into the Wadi Ha, which in turn was the head-water of the Wadi Sahba. Owing to the large catchment of 71,120 sq km (the active catchment in the Wadi Sahba is at present 18,000 sq km, including the Wadi Hanifah catchment), the long Wadi Sahba cut its bed and flowed eastwards at far as the Arabian Gulf, south of Qater (Fig 4.5). Metamorphic and igneous pebbles reported to be found in the dried valley of the Wadi Sahba by Brown (1949) give strong evidence of its dimension.

Erosion in the valley of the Wadi Hanifah proper occurred

Fig. 4·5 THE WADI SAHBA DRAINAGE, AT THE TIME WHEN THE WADI HA DRAINAGE EXTENDED INTO THE BASEMENT COMPLEX



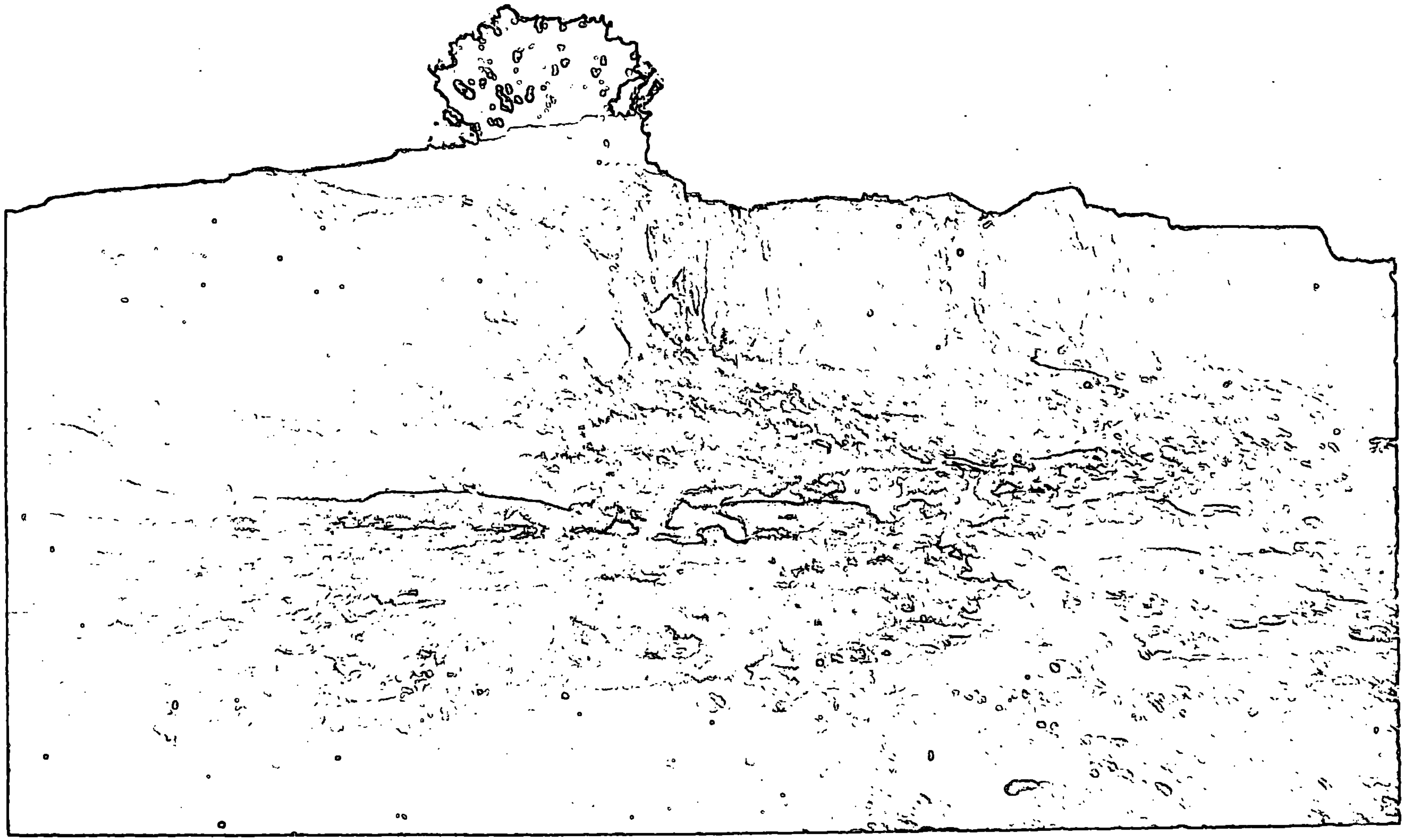
mainly in the Pliocene/Pleistocene and probably finished at the end of the Pleistocene. From the logs of five wells drilled in 1953 by Michael Baker Co across the Wadi channel one mile downstream from the Hanifah Dam, it was confirmed that the essential shape of the channel was rectangular, with steep sides and a broad base at a depth of 60 m beneath the surface of the present wadi channel (Fig 3.2).

However, alternative erosion and deposition levels related to the Quaternary Age have been traced and recorded (McCann, 1959). It was found accordingly that the channel bottom contains a very coarse irregular alluvial fill, presumably caused by erosion during a period of torrential rain and a variable stream flow. In the subsequent erosional period, the wadi cut the alluvial fill and formed a new channel. A quiescent period followed which caused the deposition of a layer of silt and clay some 30 m deep on which the present channel has acted. A few streaks and lenses of gravel show some variation in the surface water flow, but generally climatic conditions seem to have been regular. In fairly recent times, a new channel was eroded in the silt and clay, then filled gradually with gravel. The silt terraces rising above the present channel (Plate 4.1) could have been deposited during the final epoch, prior to the recent arroyo cycle. Moreover, Wolfart (1961) pointed out that the terraces in some wadis indicate sub-recent uplift, indicating a close relation between relief formations and epirogenetic movements. The deposition of the wadi, however, has been controlled by the underlying structure of the Jurassic formations.

The head-water of Wadi Hanifah starts 85 km north-east of Riyadh City. The water-parting is shared with the Wadi Al-Hisian which flows

Plate 4.1

The Silt Terrace near Al-Jubailah Village



through a gorge in the opposite direction to that of the dip slope. 16 km east of the water parting, the Wadi Hanifah can easily be distinguished as it is joined by a number of small, step-wall tributaries, which also extend to the crest of the Tuwaig Mountain (Leachman, 1914). In the 20 km stretch upstream of Al-Uyaynah village, the wadi crosses the Hanifah formation in a generally easterly direction. Here the wadi forms a rather flat valley with irregular channels of varying width (between one and 10 km), covered with alluvial material (Plate 4.2). While the drainage water in the area has a simple west-to-east flow, a break in the resistant rock of the Jubaila unit forced the flow to continue in a roughly south-easterly direction. From Al-Uyaynah downstream to Al-Ha'ir village, a stretch of more than 70 km, the wadi is controlled by dams and hand-built diversions which therefore affect the water flow and the erosion-deposition processes. Between Al-Ha'ir and Al-Kharj plain, the wadi appears to be relatively flat, and here infiltration is active. Ultimately it joins Al-Kharj plain at an altitude of 450 m above sea level and dries up in the Tawdheeheyyah Playa - a lake, to the east of Al-Kharj, at an altitude of 400 m above sea level.

Plate 4.2

The Channel of the Wadi Hanifah - upstream from Al-Uyaynah Village

CHAPTER FIVE

CLIMATE

Existing publications concerning the Arabian Peninsula seem to deal with the climatic conditions of the country in relation to the climate of the Mediterranean and, while this is broadly justifiable, the information given lacks local detail. The only organisations to make a comprehensive study of the area have been UNESCO and the F A O of the United Nations. Their publications concentrate largely on precipitation and its inter-influence with biological resources. The problem here is that such studies need to be based on and supported by a wide range of statistics and other material relating to the area, and although climatic data over long periods are available for some of the world's arid lands, no such data are available for central Arabia, including the Wadi Hanifah Basin.

For more than 400 years, the Ottoman Empire extended over the whole of the Arabian Peninsula, except the region of Nejd which was protected by great belts of sand stretching from the Great Nafud in the north, to Ad-Dahna in the east and Rub al-Khali in the south. Even after the collapse of the Ottoman Empire, the world's great powers of that period were concerned only with the Mediterranean countries and the seas surrounding Arabia. As a result, while a survey of climatic conditions was carried out in the Mediterranean Basin and the Arabian Sea, central Arabia was considered too remote for such a survey. These surveys helped to define the influence of the air masses and pressure zones which might affect the Arabian interior, but no definite statistics could be obtained from them, since their findings were based mainly on results obtained in other climatic regions, outside the area under study. Over the last four decades, studies by Thornthwait, Köppen, De Martin and Meigs have succeeded in defining various climatic boundaries, including those of the arid zone, and their investigations have paved the way for a greater understanding of the basic work needed to explain this desert like regime; from here, the necessary data can be obtained with the aid of instruments and applied research.

By using the available data, an attempt will be made in this study to avoid confusion concerning the climate of the Wadi Hanifah. An analysis will be made which refers not only to meteorological data, but also to old publications and to observations made over a long period by local inhabitants, for whom the climatic conditions of the area are vital in their constant struggle for survival. By studying these extra factors, it is hoped to throw more light on different methods of defining climatic conditions, as relating to the hydrology of the area.

5.1 Factors Affecting Climate

5.1.1 Geographical Situation

The Waid Hanifah lies in a vast, dry, hot area; the nearest water being the Arabian Gulf, some 400km to the east, and the Red Sea, about 1,000km to the west. Except for the Tuwaig Mountain, which forms its waterhead boundary to the west, the adjacent areas in all directions are rather flat, dominated by huge sand dunes and Quaternary deposits. One exception is the west where the sand dunes lies in discrete sand areas, separated from each other - for example, Nafud Kunaifethah, Nafud Ad-Dahi and Nafud As-Sir. Further westward, the Sarat Mountains form a topographical barrier which affects central Arabia, including the Hanifah region.

These topographical features affect the climatic elements of the Wadi Hanifah in the following ways:-

(i) The surrounding sand areas (in particular the Rub al-Khali) are the source of the hot, dusty winds which prevail in the late spring and summer seasons.

(ii) The western mountains of Sarat effectively shade the region from the monsoon precipitation, which falls on the western side of these mountains during the summer season.

Its location leaves the region between the influence of the Mediterranean climate system and the influence of the huge sand zone in the south in terms of effects of seasonal precipitation. However, the highlands of the Tuwaig mountain are one of the larger features of the Arabian Peninsula, and they tend to influence the surplus precipitation which passes through the north-western area of Saudi Arabia.

On a larger scale, the topography and situation, coupled with the influence of the air pressure zones to the north and east, helps the solar influence to form an area of arid climate. Due to the absence of long-term meteorological records and accurate local investigations, these conditions are not yet fully understood.

5.1.2 Pressure Zones

Existing knowledge about atmospheric pressure zones and air masses will, with care, enable us to describe the climatic characteristics of the area under study.

The pressure zones which are likely to affect the region of the Wadi Hanifah during the summer appear to be two. The low pressure zone, which prevails over the Gulf of Oman, carries over to the Arabian Gulf and the central part of Saudi Arabia, including the area of the Wadi Hanifah. A secondary low pressure zone, which lies over the area round Cyprus in the eastern Mediterranean, seems to be formed as a result of the contrast between sea and land in that area. These pressure zones give rise to the north-west, north and north-east winds prevailing in the Wadi Hanifah during the summer, particularly when the two pressures over Cyprus and the Arabian Gulf constitute a single front.

During the winter, the Wadi Hanifah region is mainly influenced by three patterns of pressure:-

(i) the high pressure which covers Central Asia and extends westwards to the western part of Iran;

(ii) the low pressure zone south of the Equator, and,

(iii) the minor low pressure zone over the Mediterranean Sea.

Whilst the pressure conditions over the Middle East seem to be variable in winter (Fisher, 1971), the three aforementioned pressure zones have a major influence on wind direction over the study area, and the Equatorial low pressure to the south draws an air current from the Asian high pressure zone, resulting in the north-westerly winds which prevail over the Wadi Hanifah. The depressions of the Mediterranean are certainly a major climatic condition affecting the Wadi Hanifah region. The depressions which come from the Atlantic in the west across the Mediterranean may not be as effective as the depressions which form over the Mediterranean itself. Thus, while the local depressions of the Mediterranean are smaller, they are of greater intensity. The tracks take a roughly west to east direction over the Mediterranean. Some depressions pass over the Northern Basin towards central Europe and southern Russia, and some pass across the Mediterranean towards the Levant, and possibly as far as Iran and northern India, before dying out over the plains of northern India (Biel, 1946). Yet others pass over the southern basin of the Mediterranean, and curve in a south-easterly direction towards the Arabian Peninsula, particularly the northern and central parts, and these latter depressions are the main source of wintry rain over the Wadi Hanifah. Their movements and frequency are irregular, and their journey across the Mediterranean to the inland areas of Levant and central Arabia takes approximately four to eight days. This frequency over the Wadi Hanifah has so far been unrecorded, but it is believed that they occur at similar intervals to those in the northern parts of the country's boundaries; for example, approximately three or four times monthly during the winter (Al-Marzouq, 1971). Under the influence of these depressions over the Wadi Hanifah region, the wind tends to be changeable, responding to the location of the depression, but once the depression passes away, it is replaced by the prevailing wind - normally in a north-west to south-east direction.

5.1.3 Air Masses

Over the year, the climate of the Wadi Hanifah is influenced by four air masses:-

(a) Monsoon air, originating over India.

(b) Maritime air, from the Atlantic.

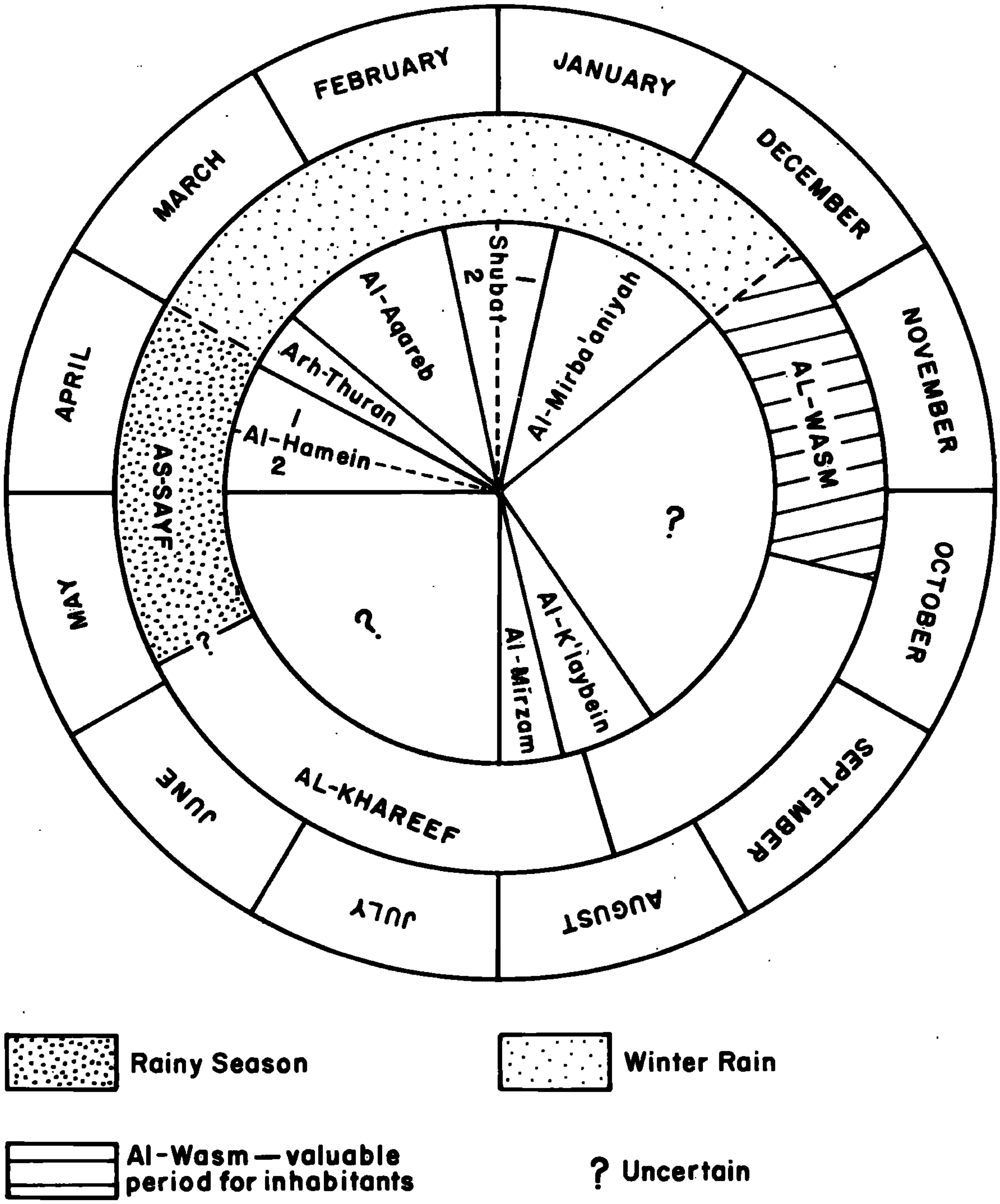
(c) Tropical continental air, from the wide desert of Rub al-Khali and the Sahara.

(d) Polar continental air from Eurasia.

From the previous section on pressure distribution and depression tracks, it is evident that the range of air masses and the intensity of their clashes are much greater in winter than in summer. Thus, from October till May the Maritime damp air from the Atlantic moves from west to east, passing through the Mediterranean and Northern Africa to the north-west of Saudi Arabia and penetrating the Wadi Hanifah region from late October and early November. The influence of the Maritime air is characterised by the comparatively small depressions which develop mainly over the Atlantic and the Mediterranean and travel to the region under study. The invasion of Maritime air during the winter modifies the climatic conditions, causing rather cloudy weather for a few days, with some spells of cold weather.

At the same time, periodic interruption by the Polar Continental air from Eurasia may cause the Maritime air to retreat westward, and the region is then occupied by a current of cold northern wind, known locally as "Nassry". When this air invades the Hanifah area the sky becomes cloudless, with brilliant stars at night, and occasionally the temperature drops to one or two degrees below freezing point. The invasion of these cold northerly air currents begins, according to the local seasonal calendar, in Al-Mirba'aniyyah, from the second week of December until the middle of January (Fig 5. 1). The air pressure

Fig 5·1 A COMBINATION OF CLIMATIC CONDITIONS AND THE LOCAL CALENDAR



becomes stable from the second half of January until about 10th February which is well known as the coldest period of the year, and is called "Ash-Shibt" (singular Shubat). It appears that when the Polar air clears away, it is replaced by the Maritime air, which continues until the end of spring.

With the coming of spring, which normally begins in the latter half of March and continues until approximately the end of April, the Tropical Continental air from the Rub al-Khali in the south begins to blow, particularly when depressions penetrate to central Arabia on a large scale. The air is pulled into the warm sector of the rapidly moving depression, formed in the Maritime air, and this wind can be compared to the Khamasin wind of Egypt, which blows from the Sahara Desert. As it is in the central part of Arabia, a few hundred kilometres north of the wide desert of Rub al-Khali, the Wadi Hanifah region enjoys two types of Tropical Continental Air. The first is characterised by sandstorms which reach the region as comparatively small whirlwinds, but which seldom last for more than 30 minutes. This weather usually occurs in March and April, with winds at gale force, and occurs very often after two o'clock when the ground temperature rises sharply. Its occurrence is usually connected with low spring clouds (Cumulus and Nimbostratus). The second occurs at the end of spring, when the currents of air flow in a south-north direction; the dust and sandstorms last for a long time.

The Tropical Continental air is interrupted from June onwards by the Monsoon air, which originates over the Indian Ocean and flows via Iran, eventually taking a north-east to south-west direction, and the two air masses bring dry, hot weather to the region. The Monsoon air brings a pleasant air current at night, which is modified by a decline in the surface air temperature.

5.2 Precipitation

While there appears to be a considerable amount of information concerning precipitation, an attempt to discover the relationship between precipitation and run-off revealed a lack of relevant data. Since the Wadi Hanifah area forms a catchment or drainage system, a number of network stations should have been installed to provide the necessary information concerning the density, duration and frequency of precipitation. Furthermore, as the drainage basin is in the Tuwaig mountain, which receives a variety of types of genetic precipitation, for example convective, cyclonic and orographic, the Riyadh Airport station, which is the nearest with detailed meteorological records, cannot give an overall picture of the types in the area. However, a great effort has been made to obtain all the available existing data, both from the Airport station and from other organisations which contributed official hydrological work. The following data have in consequence been examined:-

(i) The recorded data from Riyadh Airport station, which commenced operations in 1952.

(ii) The climatic data collected between 1941 and 1945 for the Riyadh area, giving only the average rainfall, the number of days with at least 1·0 nm rainfall, and the absolute maximum daily rainfall.

(iii) Rainfall at Riyadh for 1948, taken by the Ralf M Parsons

Company.

(iv) Climatic data, recorded by separate rain gauges in Riyadh City, Al-Jubailah and Hanifah Dam areas from 1967 onwards, by the Hydrological Department of the Ministry of Agriculture and Water.

(v) Information from a survey and investigation study carried out between 1966 and 1968 by Sogreah. A number of rain gauges were installed in different parts of Area V, including the Wadi Hanifah region. Twelve were installed in different parts of the Wadi Hanifah catchment.

(vi) General information supplied by the well-known historians of Nejd, Ibn Bishir, and Ibn Eissa (see references). Although such publications were written according to the Muslim calendar (Hijrah), the conversion method given by Freeman-Grenville (1963) is used to convert these dates to the modern calendar.

NB : No data were forthcoming for 1949, 1950 and 1951.

While this information seems substantial, its inaccuracy and lack of continuity are major obstacles. Sogreah (1968A), in their final report, gave an account of the difficulty of obtaining daily readings from the rain gauges:-

> "However, its (the instrument's) lightness and general appearance are obviously tempting to some people as more than 30% of them had to be replaced during the course of field work. Also, it is very difficult to protect these apparatus once placed in the open air, even if they are near the guardian's dwelling. . . . . They were sometimes emptied or interfered with by person unknown, so that it is not certain that all the observations made with totalisers are exact."

Accordingly, the greatest possible care is taken in considering the existing data. Though it is necessary to rely on the recorded data, some of the conditions are examined in the light of long-range observations by local inhabitants; since the climate vitally affects their livelihood, they have a knowledge of some weather conditions which have been vividly described.

5.2.1 Variation of Precipitation

In dealing with precipitation in terms of its mean annual total in any form or appearance, precipitation must be treated as rainfall. The available climatic data have failed to differentiate between one type and another, for example rain or hail.

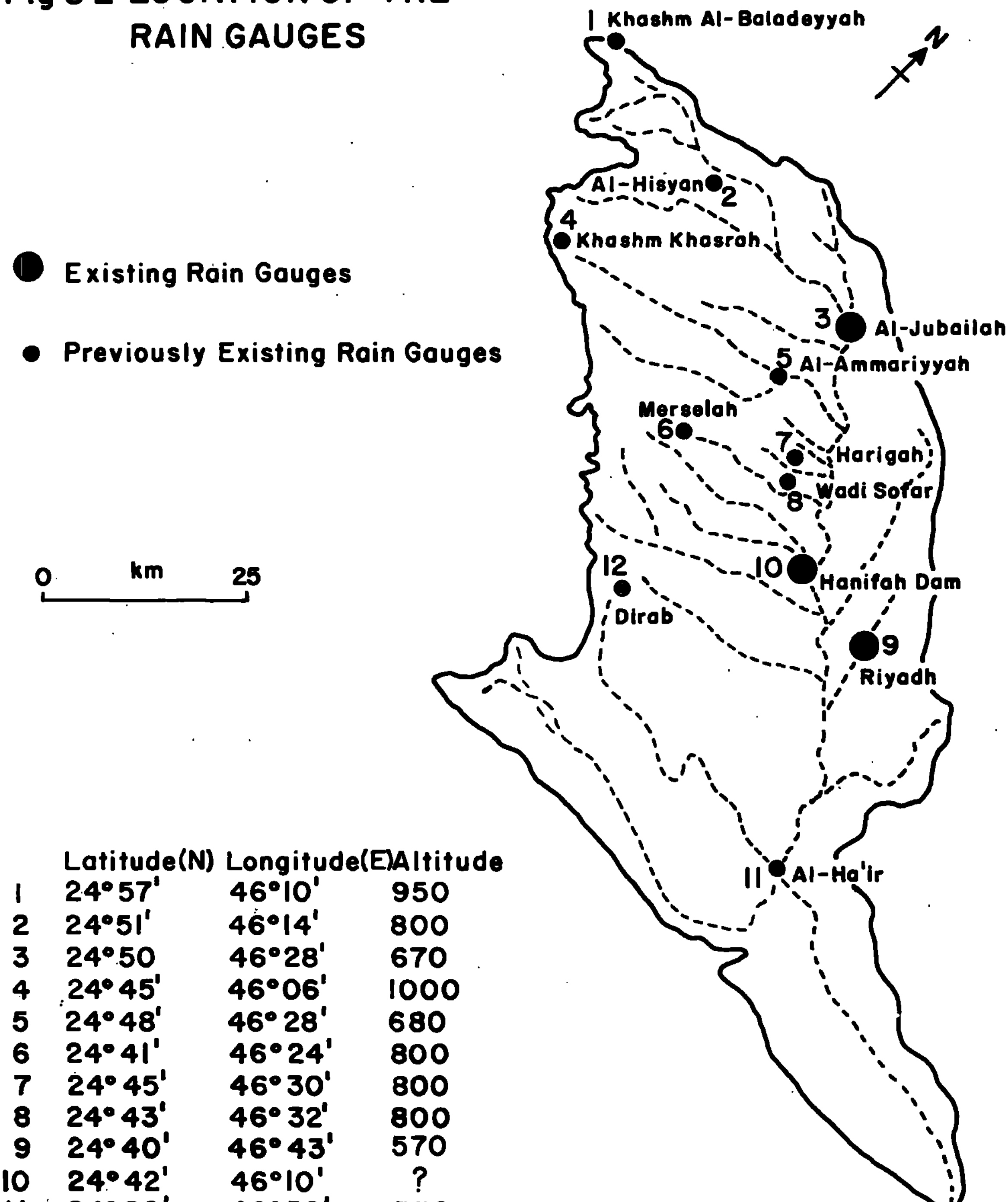
The Wadi Hanifah region broadly follows the climatic regime of central Saudi Arabia, where rainfall may occur in almost seven months of the year, and the remaining months (June to October) are almost totally without rain. The climatic data used were taken from 12 sites where the period of measurement ranges between only a few months to 20 years.

Precipitation very often occurs in the form of desert thundrstorms, which suggests that the mean annual rainfall figures give a very misleading idea of the local rainfall characteristics. Indeed, variation of rainfall density and amount occurs from place to place in the wadi. In spite of the interrupted and sparse data, the variations of the rainfall will be defined in terms of different localities and various periods of time.

(a) Geographical Variation

Data collected from a series of 12 rain gauges (Fig 5.2) over a

Fig 5·2 LOCATION OF THE RAIN GAUGES



	Latitude(N)	Longitude(E)	Altitude
1	24°57'	46°10'	950
2	24°51'	46°14'	800
3	24°50	46°28'	670
4	24°45'	46°06'	1000
5	24°48'	46°28'	680
6	24°41'	46°24'	800
7	24°45'	46°30'	800
8	24°43'	46°32'	800
9	24°40'	46°43'	570
10	24°42'	46°10'	?
11	24°20'	46°50'	550
12	24°31'	46°27'	920

period of three years indicates that the area under study shows distinct variations, both in the annual total and the monthly average. Unfortunately, due to interference, the records over the measurement period are incomplete, and the only year which appears to be comparatively complete for most of the localities is 1967. Table 5.1 gives the monthly rainfall for the 12 areas with the exception of Al-Ammariyyah, for which no records are available in that year. In six cases records are complete, but the remaining records were intermittent; the table gives information for the northern part of the catchment (Upper Wadi sub-catchment) and the eastern part. However, these records should be considered carefully with regard to the type of rainfall and the rain belts. The comparatively heavy annual rainfall in the northern part was due to the wintry rainfall which occurred particularly in November, while the high volume of rainfall at Riyadh was due to the early spring that year, in late March, April and May. Though high monthly figures may distinguish the rainy season, rain normally falls on only one or two days each month, leaving the rest of the month almost dry, with a minimal amount of rain. Thus the volume of rainfall is almost totally dependent on thunderstorms, which are characterised by their narrow path and varying intensity.

It can be assumed that in 1967 the cyclonic rainfall in the winter was concentrated over the northern part in the form of comparatively widespread thunderstorms, which travelled from north-west to south-east (Fig 5.3). Most of the rainfall over Riyadh and Hanifah Dam occurred in the early spring of that year, with the narrower belts being observed elsewhere. It is rather difficult to distinguish the gradient of rainfall from only one complete year's measurements, and calculations are hampered by the inefficient distribution of the rain gauges.

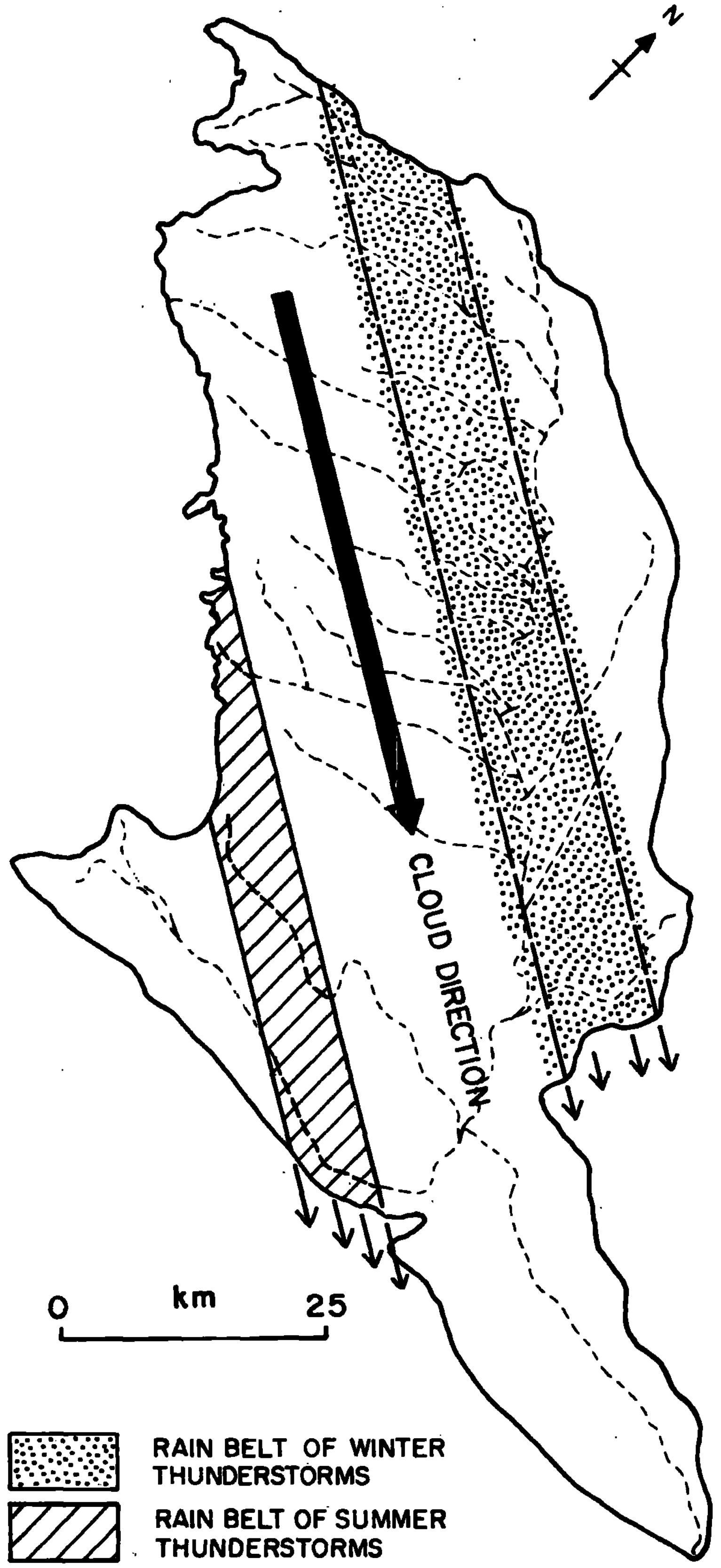
TABLE 5.1

The Monthly Rainfall of the Wadi Hanifah Basin in 1967

	January	February	March	April	May	June	July	August	September	October	November	December	Total
Khashm Al-Baladiyyah	6·5	8·5	11·5	21·0	13·0	0	0	0	0	0	90·5	0	151·0
Al-Hisyan	4·0	12·5	16·0	19·0	-------	-------	-------	no data	-------	-------	97·5	0	(149·0)
Al-Jubailah	0	11·5	22·5	31·0	11·5	0	0	0	0	0	60·5	0	137·0
Khashm Kharsa	-- no data --		0	0	0	0	0	0	0	0	3·0	0	(3·0)
Al-Ammariyyah	-------	-------	-------	-------	-------	-------	-------	no data	-------	-------	-------	-------	-------
Merselah	1·0	9·0	20·0	29·0	17·5	0	0	0	0	0	20·0	0	96·5
Harigah	0	10·5	19·5	22·0	18·0	0	0	0	0	0	16·5	0	86·5
Wadi Sofar	-----	no data	-----	16·5	26·5	19·0	0	0	0	0	18·5	0	(80·5)
Riyadh	0	2·6	84·3	44·3	69·5	0	0·5	0	0	0	16·0	0	216·7
Hanifah Dam	0·6	6·2	17·1	56·7	22·6	0	0	0	0	0	22·3	0	125·5
Al-Ha'ir	-----	no data	-----	35·5	22·0	0	0	0	0	0	8·0	0	(56·5)
Dirab	-----	no data	-----	4·0	-	21·0	0	0	0	0	22·5	0	(47·5)

Sources: Records of the Hydrology Department of the Ministry of Agriculture and Water, Riyadh
Sogreah (1968D)

Fig 5·3 APPROXIMATE RAIN BELT OF A SINGLE THUNDERSTORM



(based on personal observation)

However, even this short measurement throws some light on the existence of two local factors which should be taken into consideration:-

(i) The relative height of the western boundary, represented by Tuwaig mountain, does influence the adiabetic process of the cloud. The altitude of the crest of the mountain within the Wadi Hanifah Basin ranges between 900 m in the north and 750 m above sea level in the south. From the one year's climatic data, the effect of the Tuwaig mountain was recognisable on the Khashm Al-Baladiyyah, Al-Hisyan and Dirab (Fig 5.4), but the effects of such a short period of data recording must be dealt with in the light of the individual bands of thunderstorm cloud which take a more or less identifiable track over one part of the catchment for one single rainy period, which may be only a few hours or even a few days.

(ii) The other factor is seen in Riyadh City, which occupies an area of more than 70 sq km. Being an urban area with contrasting features of parks, streets and buildings, etc., circulation of local wind and air pressures could be influenced accordingly. In 1967, Riyadh was the only station out of 12 rainfall stations in the region where any rain was recorded during the summer.

The rest of the Wadi basin has comparatively low rainfall owing to its location away from the orographical effect of the mountain.

(b) Variation with Time

(i) Cyclic Variation

The available data from Riyadh Airport appear to cover too short a time to permit the detection of any definite cycle of rainfall. The measurements begun in 1948 recorded 88 mm of rainfall for one year;

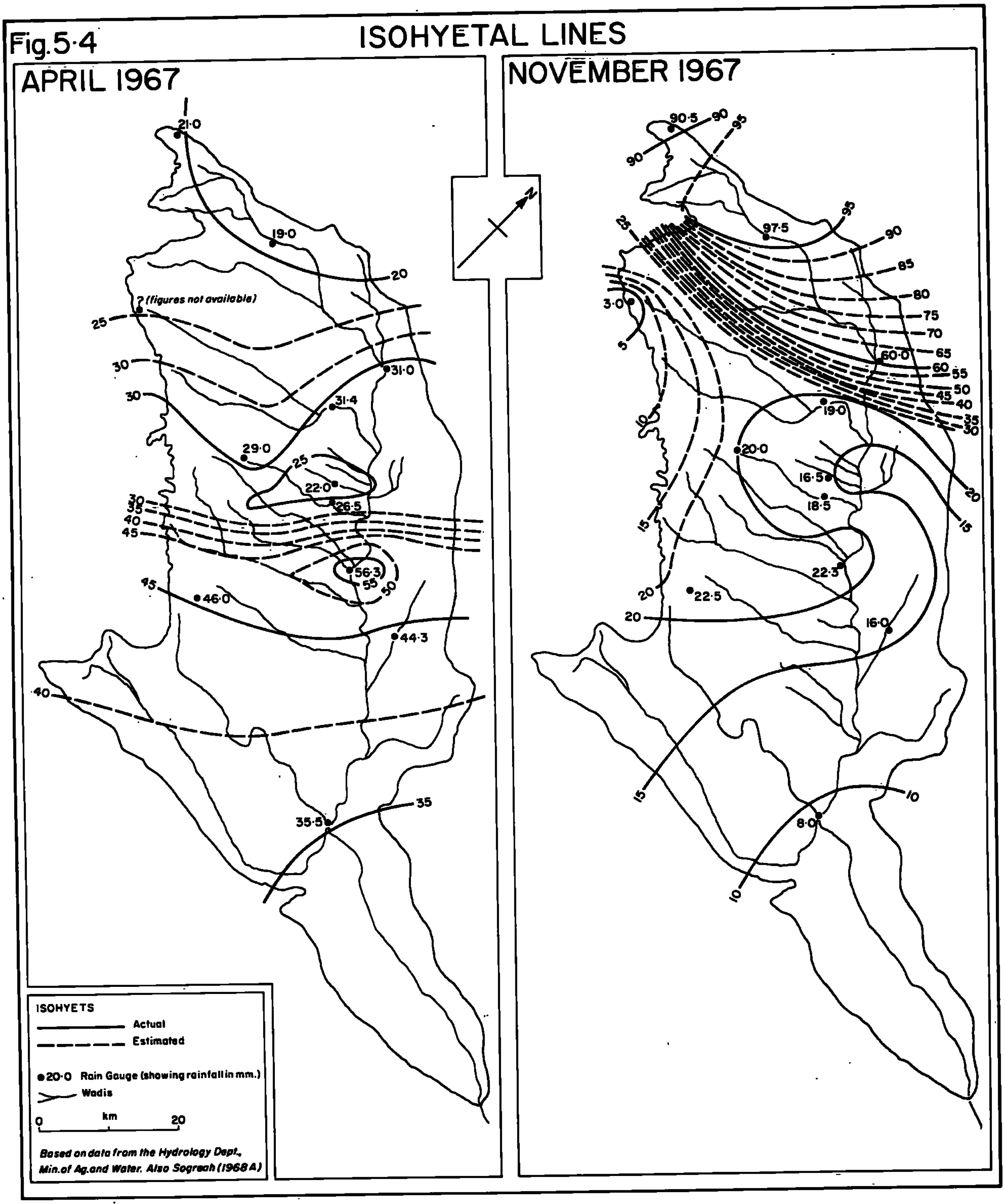


Fig.5·4
ISOHYETAL LINES
APRIL 1967
NOVEMBER 1967
N
21·0
19·0
20
? (figures not available)
25
30
31·0
31·4
29·0
22·0
26·5
35
40
45
56·3
55
50
46·0
44·3
35·5
90·5
90
95
97·5
85
80
75
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60·0
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55
50
45
40
35
3·0
5
10
19·0
20·0
16·5
18·5
15
22·3
22·5
16·0
8·0
ISOHYETS
Actual
Estimated
20·0 Rain Gauge (showing rainfall in mm.)
Wadis
0 km 20
Based on data from the Hydrology Dept., Min. of Ag. and Water. Also Sogreah (1968 A)

the recordings were recommenced in 1952, and successive years showed large variations in rainfall. Out of 11 successive hydrological years* from 1954/55 to 1966/67, the total annual rainfall was less than the monthly total of February 1953, and within this period the amount falling in five successive hydrological years ranged between 92·3 mm and 45·8 mm. Though such variations might be considered accidental, historical information over three centuries roughly conforms to this cycle. Ibn Bishr (1971) and Ibn Eissa (1966), who wrote about political and social aspects in the central part of Saudi Arabia, mentioned years of extreme drought, and then years of successive rainfall, which are recognised in a hydrological sense as "wet years". These were known locally as "Kah't" (years of extreme drought) and "Rej'an" (wet years). From 1637/38 (1047 AH) until 1784/85 (1199 AH), ten different "kah'ts" hit the area violently, and caused the loss of many human lives and the destruction of domestic animals. The time interval between two successive drought periods is given in Table 5.2.

TABLE 5.2

Time Variations of Kah'ts and Rej'an between 1637/38 and 1872/73 (1047 to 1289 AH)

Years :	<2	2-10	10-20	20-30	30-40	40-50	50-60
Total No of droughts (Kah'ts)	1	-	5	3	-	-	1
Total No of wet years (Rej'an)	2	4	4	3	2	-	-

* From November to October.

Most of these dry years were given identifiable names, for example, Habran and Doulab for droughts which occurred in 1654/55 (1965/66 AH) and 1782/83 (1197/98 AH) respectively. It is interesting to note that four of these droughts each lasted for at least three successive years, two for two years and the rest for one year each. During the recorded period of Nejd historian, i.e., about 235 years, the years which can be classified as wet years only amounts to 15 years. However, the important point is that an average or mean annual rainfall, without sufficient records, is not totally accurate. Alternatively, it can give the annual rainfall regime, leaving a margin for variation.

(ii) Annual and Seasonal Variation

As has previously been mentioned, the area under study receives almost all its annual rainfall in the winter and spring seasons, as a result of a combination of cyclonic and convectional processes, combined with the orographic influence of the Tuwaig highlands. The summer and autumn seasons are generally dry with clear skies and high temperatures.

The average annual rainfall recorded over a period of 16 years at Riyadh Airport between 1952/53 and 1968/69 was about 110 mm. Variation between years is rather high, and the fluctation between two successive years has been as high as 84%. This type of fluctation has always created an unstable balance between the inhabitants and their ecological environment. In one period the region may enjoy a semi-arid climate, facilitating abundant growth of vegetation, while in other seasons it may remain completely dry in terms of its eco-environment. Thus relating the amount of rainfall to the contribution of run-off is extremely important in terms of grazing plants. Moreover, as the land is used for cultivation and grazing, calculation of the amount of rainfall necessary to produce a fodder harvest over a specified period will help to define the limits of the wet and dry years. This method will help to calculate the effect of rainfall upon agricultural and grazing land; unfortunately, the period for which data are available in the Wadi Hanifah region is too short to indicate the percentage of wet years out of the total, except for Riyadh Airport station. However, if allowances are made for the difference between the effectiveness of seasonal rainfall, it is estimated by Sogreah (1968A) that every year that has one week or more of 30 mm rainfall can be considered as a wet year, as this amount of rainfall can produce a fodder harvest, and any year which has less than 30 mm rainfall is classified as a dry year.

Statistics from Riyadh Airport indicate that considerable fluctuations exist. Rainfall could be in excess of 30 mm in a period of one week; and one day had four times that amount, as happened in February 1953 when 134·3 mm was recorded.

However, Ibn Bishir (1971) and Ibn Eissa (1966) mentioned that in 1809 (1224 AH) and 1819 (1234 AH) .. torrential rains of long duration occurred in July in the Nejd Province, and as a result the Wadi Hanifah and Wadi Ar-Rummah of Al-Kasseim were flooded. Such summer rain is unusual according to existing climatic data, but it certainly occurs occasionally, and older inhabitants in some villages can recall such a phenomenon called "Khareef" taking place once or twice during their lifetimes, probably one year within a period of 30 to 50 years. Thus climatic records going back many years must be studied to widen our knowledge of the climatic elements of the region.

In Table 5.3, data from the three stations of Riyadh, Hanifah Dam and Al-Jubailah are analysed to meet the requirements of this study. It can be seen that the percentage of wet years (out of the five years mentioned in the table) in Riyadh and Hanifah dam is almost the same as for Riyadh Station before 1969, i.e., $\frac{6 \text{ wet years}}{10 \text{ total years}}$ while at Al-Jubailah station, the percentage is $\frac{4 \text{ wet years}}{10 \text{ total years}}$. A possible error which could affect this generalisation is that rainfall of more than 30 mm may occur only on one day or one week, while the rest of the year is almost dry; therefore, a number based on the total of rainfall per day is established on the table to clarify the effectiveness of rainfall in terms of run-off and benefits to grazing land. Thus, when low density rainfall occurred for a long period, while only a minimum volume of run-off could be expected, grazing land would flourish for long periods of the year - for example, Riyadh, 1969. If the amount of rainfall is high on only one or two days per year, while the remaining days have only low density rainfall, run-off is expected, but the effect on grazing lands is variable. In addition, the occurrence of a large volume of rainfall on one or two days per year indicates the type of spring rainfall which was observed in Al-Jubailah in 1972.

In short, the Wadi Hanifah rainfall occurs mainly in the winter and spring; the winter rainfall consists of one peak in January and February, while the spring rainfall extends from March to the end of May, with a further peak in April. As a result of the orographic condition caused by the Tuwaig Mountain the average total rainfall exceeds 100 mm. The summer and autumn seasons are considered a dry period, although a trace of rainfall (less than 5 mm) has been recorded in some years for

TABLE 5.3

Rainfall in the Area of Wadi Hanifah (1969-1973)

Station	Year	Total Annual Rainfall	No of Weeks when Rainfall Exceeded 30mm	No of Rainy Days	Number of Days (in mm) when Rainfall was:-								Type of Year
					<5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
Riyadh	1969	143·4	1	34	29	5	-	-	-	-	-	-	Wet
	1970	12·6	-	10	8	2	-	-	-	-	-	-	Dry
	1971	90·3	1	19	14	2	1	-	1	1	-	-	Wet
	1972	163·2	1	25	20	2	2	1	-	-	-	-	Wet
	1973	54·7	-	12	8	3	1	-	-	-	-	-	Dry
Hanifah Dam	1969	127·5	2	31	25	3	1	-	2	-	-	-	Wet
	1970	19·1	-	8	7	1	-	-	-	-	-	-	Dry
	1971	90·4	1	16	10	3	2	-	1	-	-	-	Wet
	1972	158·0	1	30	22	4	1	-	2	-	1	-	Wet
	1973												(Dry?)
Al-Jubailah	1969	98·5	-	22	16	4	2	-	-	-	-	-	Dry
	1970	21 0	-	10	10	-	-	-	-	-	-	-	Dry
	1971	85·7	2	9	4	1	1	3	-	-	-	-	Wet
	1972	137·7	2	18	12	2	2	-	1	-	-	1	Wet
	1973	63·0	-	7	4	2	1	-	-	-	-	-	Dry

Sources : Riyadh Airport Record (1969-1973); The Ministry of Agriculture and Water (1969-1973); Sogreah (1968A)

July. (Table 5.4).

5.2.2 Types of Precipitation

A classification of precipitation types can be made either on the basis of form or appearance (for example, liquid or solid), or on the basis of genesis (for example, cyclonical, convectional and orographic). In order to define the types in the Wadi Hanifah area, we must examine both these classifications.

In consequence of the general climatic conditions in the area under study the liquid type is the main form of precipitation. The dominant type is undoubtedly showery rain, which occurs during the rainy season and becomes intense in the spring. This type is very important in producing flooding in the Wadi streams, and in some years may cause substantial damage to the property of the inhabitants, particularly when the rain is accompanied by a high-velocity wind. Fog and dew also occur in minimum volume; no recording of dew can be traced, but dew can be observed in the early morning on the leaves of cultivated plants and trees, and may sometimes leave damp traces on hard ground. Fog rarely occurs in the Wadi Hanifah, forming only very occasionally during the winter months of January and February; over a thirteen-year period, only 22 days were foggy. The monthly average seems to be comparatively high in January, and 50% of all fog occurs during this month (Table 5.5). However, fog is very rarely noticed in the city of Riyadh itself, due to urban obstruction; but it can easily be seen, when it occurs, in some places near the channels and cliffs of the main Wadi. The duration ranges between one and six hours.

TABLE 5.4

The Maximum and Average Monthly Rainfall in Riyadh Airport Station

(1952/53 - 1966/67) and (1948)

	Winter				Spring			Summer			Autumn	
	Nov	Dec	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct
Monthly Maximum	44·0	70·0	57·2	134·3	84·3	51·0	69·0	-	2·00	-	-	-
Monthly Minimum	0	0	0	0	0	0	0	0	0	0	0	0
Average	12·1	13·6	14·0	15·9	15·5	17·5	13·4	0	0·15	0	0	0

Sources : Riyadh Airport Records
: Ralf M Parsons Company (1958)

TABLE 5.5

Number of Days with Fog in the Riyadh Airport Station

(1961-1974)

Year	J	F	M	A	M	J	J	A	S	O	N	D	Total
1961	-	-	-	-	-	-	-	-	-	-	-	-	-
1962	-	-	-	-	-	-	-	-	-	-	-	-	-
1963	-	-	-	-	-	-	-	-	-	-	-	-	-
1964	-	-	-	-	-	-	-	-	-	-	-	1	1
1965	----------				Data unavailable							----------	
1966	2	2	-	-	-	-	-	-	-	-	-	1	5
1967	2	-	-	-	-	-	-	-	-	-	-	-	2
1968	-	-	-	-	-	-	-	-	-	-	-	-	-
1969	5	1	-	-	-	-	-	-	-	-	1	-	7
1970	-	1	-	-	-	-	-	-	-	-	-	-	1
1971	-	-	-	-	-	-	-	-	-	-	1	-	1
1972	-	-	-	-	-	-	-	-	-	-	-	-	-
1973	-	-	-	-	-	-	-	-	-	-	3	-	3
1974	2	-	-	-	-	-	-	-	-	-	-	-	2
Total	11	4	-	-	-	-	-	-	-	-	5	2	22

Source : Riyadh Airport Station

The only solid precipitation is hail, which is associated with the convectional clouds which occur only in spring; hailstones falling in the area range between 5 and 20 mm in diameter, and sometimes the density of the hail is so great that it can cover the surface of the ground in a few minutes.

As previously stated, the bulk of precipitation in the Wadi Hanifah region occurs as a result of the lateral penetration of maritime air. It is generally accepted that the formation of cloud and occurrence of precipitation can be subdivided, in terms of genesis, into three types:-

(i) frontal or depressional;

(ii) orographical;

(iii) convectional.

Such subdivision in the Wadi Hanifah area is difficult, as two or three of these conditions may occur together in a short period. Nevertheless, in a broad sense, the cyclonic convectional types relate to the seasons. There is a tendency for the cyclonic type to occur in the region during the first half of the rainy season, i.e., from November to February; such a frontal or depressional rainfall results from a horizontal convergence of air in a depression which overlies colder, denser air. These phenomena are common during the winter when the cloud in front of the depression is very high (mostly cirrus or cirrocumulus types) accompanied by a southerly gradient wind. These high clouds may cover the sky for a few hours or even a whole day, and these are followed by cumulonimbus clouds, increasing in thickness as they approach the area. When these clouds cover the sky, lightning is often observed, as most of the region's rainfall is associated with thunderstorms.

The convectional type can be observed in the spring, i.e., March, April and May. When the sun warms the ground surface, it causes a condition of instability in the air which leads to ascending pockets of air that cool adiabatically to below the dew point. However, while this is common in the warm, moist, tropical climate, it is controlled in the area under study by the moist air which is brought within the maritime influence. The formation of clouds is observed mainly at noon, although they may begin to gather around 11 00 a m. Around 2 00 or 3 00 p m, the clouds appear to be atrostratus in the front (in the case of a thunderstorm) and cumulonimbus in the middle, with an almost sharp rear. The convectional-like type of thunderstorm cloud appears to have a smaller size and comparatively low height; the density of the rainfall is great and the shower droplet may exceed 2 mm in diameter; occasionally the warm air becomes unstable, resulting in hailstones.

It is therefore thought that the impact of the maritime air is the original source of the convectional rainfall in this area in both seasons. This conclusion stems from the fact that the direction of movement of clouds in winter and spring is more or less the same - from west to east.

The orographic precipitation, as such, is not individually recognisable. That is to say that the relatively high topographical features of the Tuwaig Mountain have further effects upon the density of rainfall when comparison is made between the amount of rainfall which occurs in the mountain itself and the adjacent areas, as has been stated (see Figure 5.4).

5.3 Evaporation

The Wadi Hanifah is a region where actual evaporation is comparatively small, not because evaporation is naturally low, but because the region becomes an almost arid zone for most of the year, and surface water as a source of evaporation is extremely scarce. In the summer and spring, however, the region has a high potential rate of evaporation.

The major obstacle when dealing with evaporation, as with other climatic conditions, is that, while humans can adjust to almost any situation and use it to their own advantage, this particular phenomenon is not easy to control owing to the complicating factors that work in correlation with each other, despite some minor success in protecting water reserves by various methods, for example, mono-molecular layers, etc (Ward, 1967). While evaporation is a constant and continuous process, its effect upon the area under study can be seen most clearly when water is within easy reach, either as a free water-body or a few feet below the ground. This circumstance occurs only when the region has a sufficiently large surplus of rainfall to constitute an actual flood. In accord with the scope of this work, evaporation will be dealt with in terms of annual and seasonal volume, and also with regard to its impact upon dams and irrigation water.

5.3.1 Annual, Monthly and Daily Evaporation

The measurement of evaporation, as opposed to precipitation, has not received sufficient attention during the last two decades, probably due to the common lack of interest in the subject in the country. Evaporation in the Wadi Hanifah was estimated in the 1950's and early

1960's by foreign consultants and has been subjected to technical measurement only over the last few years. The only two bodies to give recorded measurements for evaporation are Sogreah (during their 1966 and 1967 investigations of the Dirab area near the water head of the Wadi Liban tributary in the western highland of the catchment), and the Hydrology Department of the Ministry of Agriculture and Water for Riyadh area. In spite of the short period covered by these two measurements, they show contrasting features of evaporation (Table 5.6).

The total annual evaporation in the Dirab area reached 4,659 mm, while the Hydrology Department records show the annual average evaporation for Riyadh area between 1968 and 1971 inclusively to be 2,608 mm. Such a large difference between two areas with a distance of less than 30km between them is caused partly by the type of instruments used by Sogreah and the Hydrology Department. While Sogreah investigations were carried out by a class A pan, the Hydrology Department used a Colorado pan. The ratio between the two instruments is not actually known, but it is estimated to be around 80%. It is also caused by the influence of local geographical factors in the two localities. Since the Dirab area is located near the crest of the Tuwaig Mountain with an altitude of more than 910 m above sea level, its greater exposure could be responsible for the comparatively high rate of evaporation. The comparatively low rate of evaporation at Riyadh area, which represents the low land of the drainage basin, was caused by a variety of meteorological factors as a result of microclimatic conditions, as well as the low altitude (approximately 600 m above sea level), wind velocity, and relative humidity; ground and solar radiation are modified by the

TABLE 5.6

Monthly Evaporation at Riyadh (1968-71), and Dirab, (1967)

Station	Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Riyadh	1968	104	98	202	203	224	288	330	315	250	172	123	98	2407
	1969	68	97	194	223	319	369	401	357	270	197	114	100	2709
	1970	93	134	195	277	342	354	355	326	251	186	117	81	2711
	1971	102	142	202	216	275	336	351	316	258	201	120	86	2605
Average		91·75	117·75	198·25	229·75	290	336·75	359·25	328·50	257·25	189	118·50	91·25	2608
Dirab	1967	195	225	311	335	471	627	634	611	486	401	196	167	4659

Source : (1) Hydrology Department of the Ministry of Agriculture and Water, for the Riyadh Data
(2) Sogreah, 1967, for the data on Dirab

contrasting features of the urban and cultivated areas, which provide additional shelter.

Monthly evaporation appears to be at maximum in July in both Riyadh and Dirab, and at minimum in December or January.

Evaporation in the rainy season (from November until the end of May) is approximately 40% of the total annual evaporation; within this period, the evaporation increases sharply during the spring period, i.e., between March and May, while evaporation in the dry season, i.e., from June until the end of October, is accelerated by the high temperatures and the cloudless skies during these months.

The daily evaporation rates differ according to the season; in winter the daily evaporation is in the region of 5 mm, as recorded by Sogreah, while in summer the daily evaporation rate could be six times as high as the winter rate.

5.3.2 Evaporation from Dams and Irrigated Areas

The man-made reservoirs in the Wadi Hanifah proper and its main tributaries are the main areas for evaporation. Flood water is usually controlled behind seven impound dams until it eventually disappears by virtue of evaporation and infiltration. The moisture in soil, either irrigated fields or barren lands within the Wadi Basin, is also affected by evaporation.

In practice, evaporation in the Wadi Hanifah occurs when an available amount of water and moisture can be evaporated, and the rainy season is the main time when this process takes place.

As floods normally occur during the winter and spring, accordingly evaporation increases during the spring, when the solar radiation is free to reach the surface of the water. Usually, the wadi is filled with flood soon after a substantial run-off reaches the main stream; and due to the short duration of the flood, no attempt has yet been made to determine the actual amount of water lost by evaporation, although the ratio of evaporation is probably greater in the shallow moving flood than in the still water behind the dams. In other words, solar and ground radiation, coupled with the circulation of air, accelerate the rate of evaporation in the shallow depth of the flood blanket along the stream. While, behind dams, the small size of water surface and the relatively high depth of water help in decreasing the amount of evaporation.

Local geographical factors affecting evaporation of the flood water in the seven dams of the wadi are nearly similar in terms of orientation, depth, area and surrounding relief environments.

Accordingly, the main Wadi Hanifah Dam is selected to be the subject of the following discussion.

Between April 1965 and May 1972 the Dam received about 53·40 x 10^6 cu m from 17 floods with varying volumes of water (Ministry of Agriculture and Water, 1973). The evaporation rate was observed through an evaporation pan in the area, but the daily readings were carried out only when the lake was full of flood water. Table 5.7 gives the volume of water evaporated against the flood accumulated behind the dam during the period of recording. It must be stated, however, that the evaporated water figures given in the previous Table ought to be treated only as a guide to the ratio between the average volume of flood and the amount of water evaporated. With regard to the

TABLE 5.7

Volume of Evaporated Water from the Reservoir of Hanifah Dam (1965-1972)

(In 10^6 cu m)

Period of Recording	Water Evaporated	Volume of Flood
23rd April to 10th May 1965	0·031	11·27
6th November to 29th December 1965	0·04	2·62
5th to 14th May 1967	0·005	0·16
24th November 1967 to 10th February 1968	0·085	15·64
14th April to 21st May 1968	0·094	6·79
16th January to 7th February 1969	0·011	1·52
11th April to 31st May 1971	0·082	7·39
29th March to 1st May 1972	0·08	7·92
Total	0·428	53·40
Mean volume	0·0535	6·675

Source : Hydrology Department of the Ministry of Agriculture and Water, 1973 total volume of the evaporated water ($0 \cdot 428 \times 10^6$ cu m) the ratio appears to be relatively low, but if we evaluate a single flood (for example, 5th May 1967) in comparison with the amount of water evaporated in the same period, the ratio tends to be comparatively high. Nevertheless, when considering the period of measurement of evaporation of a single flood, the mean value is $0 \cdot 0535 \times 10^6$ cu m per flood. Before statistics were recorded, the consulting companies (including some of the water advisers in the Ministry of Agriculture) believed that loss by evaporation was a major obstacle to the conservation of flood water in dams, but this hypothesis appears to have been exaggerated. The annual rate of evaporation, however, is relatively high, but because of the short time in which the water is controlled by the dam (between ten and 60 days approximately), the amount which might be evaporated is not sufficient to cause alarm.

The low rate of evaporation in the main dams of the wadi proper and its various tributaries is, as previously stated, influenced by local geographical factors, the most important being the size and shape of reservoirs (see Plate 6.1). All dams on the Wadi Hanifah drainage were constructed in a narrow section of the wadi where the cliffs of the channel around and behind the dam are rather high, thus making the reservoir rectangular in shape.

The depth of the water varies according to size and shape, and ranges between 0 m in the upper end of the reservoir to a minimum of 3 m, such as in the Sorfar Dam, and a maximum of 8 m, as in Nimar Dam. The depth near the dam may reduce the rate of evaporation of water, and this reduction stems from the fact that the greater the depth of the water, the greater the difference between the air temperature and the water temperature, the main controlling factors in evaporation. The degree of water pollution appears to influence the rate of evaporation, depending on the percentage of total solids (De Wiest, 1965); while the flood water maintained in the reservoir is fresh water, it is thought that the fine silt and deposits, along with the total solids which have not so far been tested, may proportionately reduce evaporation. Finally, the surrounding relief of the reservoir, for example the high cliffs on either side, provide shelter against the local surface whirlwinds which move in the area during the rainy season in spring.

The volume of evaporation in the irrigated lands depends on the evaporation rate, the size of the area concerned, and on the water applied to the land. While the evaporation rate is taken mostly from irrigated lands (for example, Dirab and Riyadh), the rate on the cultivated zones can be affected by local environmental conditions. The supply of water also raises a major obstacle to any estimation of the evaporation rate, due to the availability of shallow underground water, which relies on seasonal rainfall (see Chapter 7, The Alluvium Aquifer). Nevertheless, an evaluation of water evaporating from such land (excluding transpiration) would appear to be useful.

Unlike evaporation from dams, the evaporation here is caused by the excessive production of ground water for the irrigation of date gardens and alfalfa crops. According to the only agricultural investigations so far carried out by the Ministry of Agriculture and Water in 1964, the constant irrigated land is in the order of approximately 3,262·7 hectares (see Table 1.1). Forty per cent of the area consists of constantly irrigated plants, for example palm trees and alfalfa. It is believed that a considerable volume of water is evaporated, particularly during the summer when the evaporation rate reaches its maximum. McCann (1959), when studying the cultivated area in the upper part of the Wadi, estimated that, from a volume of $2 \cdot 1 \times 10^6$ cu m of water applied to an area of 752·6 hectares, a total of about $0 \cdot 9 \times 10^6$ cu m of water could have evaporated in 1958, and this drew attention to an unexpected loss of water by evaporation. However, unless such discoveries are technically analysed, substantial errors may be made in any estimation.

5.4 Temperature

Temperature is the second most important element after rainfall, strongly affecting not only the biological characteristics of the region, but also human behaviour and lifestyle. Unlike the seasonal identity of the coastal areas of Saudi Arabia, which are affected by the neighbouring water bodies, the seasonal identity of the Wadi Hanifah region is governed by the variation between two distinct periods of summer and winter, for it lies one degree latitude north of Cancer, and a distance of approximately 370 km from the Arabian Gulf, which is the nearest sea. Also, the bulk of the wadi area stands at the eastern foot of the Tuwaig mountain, and these geographical factors provide considerable modification to the temperature characteristics of the region.

In practice, the variations of seasonal and diurnal temperature are rather more important than the annual average; whilst the latter can give a broad impression of the regime in terms of global distribution, the shorter period is more accurate. However, according to the Riyadh Airport data, the mean annual temperature for the period between 1959 and 1970 inclusive ranges between 23·5°C and 26°C. The monthly average mean temperature for the same period ranges between 34·48°C in July and 14·52°C in January. The mean annual temperature of the Dirab area, near the escarpment of the Tuwaig mountain, was 23·3°C for the only recorded year, 1967 (Sogreah, 1968D).

The daily temperature range appears to be very high. According to 16 years' data recorded at Riyadh Airport, the absolute maximum and absolute minimum recorded temperatures have a difference of 51°C (Table 5.8). Such variation in temperature is not apparent every year, but it is rather important in terms of agricultural crops and plantations. In some years, for example, heavy losses were sustained in the tomato crop due to the low temperature, which dropped to 2°C at Riyadh and -4°C at Dirab in 1968. Low temperatures in winter are caused mainly by the interference of the dry cold air current from central Asia, and the period between 10th January and 15th February, known as Ash-Shubt, is definitely the coldest time, when the northerly wind may blow for a considerable number of days and be coupled with clear skies and a chance of some frost. in contrast, the summer period is generally very hot, except for a few nights when the region enjoys a mild northerly wind, and the most extreme limit of temperature used to result in the loss of human lives in both winter and summer.

Diurnal variation is very noticeable during any day of the year; unfortunately no statistics are available, but personal observations have shown that the range may reach 15°C. Such variations in temperature in

TABLE 5.8

A. The Limited Daily Temperature (the Highest and Lowest Temperature, °C) recorded in the Period 1957-71 at Riyadh Airport

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Absolute Maximum	30	35	37	42	45	46	47	49	45	41	35	31
Absolute Minimum	-2	0	6	8	13	18	19	21	17	10	5	-1
Difference	32	35	31	34	32	28	28	28	28	31	30	32

B. The Average Mean Temperature in the Period 1957-1971 at Riyadh Airport

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual Mean
Average Mean	14·52	16·42	20·63	24·92	29·98	33·88	34·48	34·28	31·40	25·83	19·61	14·78	25·06

Source : Riyadh Airport Station

one day, especially during the summer, affect all aspects of life; in order to escape the persistently high afternoon temperature, schools, shops and offices begin work as early as possible, for example between 06 00 and 08 00 a m, and after 2 p m human activities slow down considerably. Several open-air cafes outside the capital city on the Riyadh-Taif Highway in the west and on the Riyadh-Dhahran Highway in the east flourish in the summer months, as a result of people taking advantage of the late evening fresh air, whereas in the winter these cafes barely exist.

The temperature gradient within the area under study decreases from east to west; the exposed highlands of the Tuwaig enjoy a comparatively low temperature, while Riyadh city's microclimate varies according to its different districts. The Malez area with irrigated garden houses, enjoys a modified temperature, while in contrast the central part and the remaining sectors of the city, where wide streets with comparatively high ground and solar radiation prevail, have very high temperatures.

5.5 Humidity

Relative humidity, like other climatic elements, is formed and modified by the synoptic climatic regime, coupled with the surrounding geographical environment. The humidity element in the Wadi Hanifah differs in its range and limits from other areas in the country, due to the location of the area, far away from the sea, with the periodic invasion of alternating warm or cold and dry air currents (for example, Continental Tropical Air, or Continental Polar Air, and occasionally the penetration of the moist Maritime Air), which are responsible for the fluctuation of the relative humidity.

The mean annual relative humidity in Riyadh Airport for the years 1959 to 1971 inclusive ranged from 22·8 in 1970 to 43·2 in 1964, with an annual mean for the whole period of 31 5%. On the other hand, in the Tuwaig mountain (represented by Dirab) the mean annual humidity is somewhat different : according to the figures for the only year when data were recorded by Sogreah (1967), the mean annual was in the order of 40·1%. In the same year, Riyadh Airport had an annual mean of 29·5%. In comparison, Jeddah Airport, on the western coast of Saudi Arabia, had a recorded annual mean of 58% for the period 1959 to 1970, giving an annual mean for the whole period of approximately 62%. Thus, while the coastal areas have a rather high rate of humidity, the Wadi Hanifah region enjoys a lower volume of relative humidity. The highest monthly mean figure ever recorded at Riyadh Airport Station was 63%, in January 1965. January has the highest monthly mean for the whole period, with an average of 48·58% (Table 5.9). Within a single year, however, any one month of the rainy winter season (November to February) could have the highest recorded mean.

The absolute maxima and minima of relative humidity show contrasting figures. For example, in April 1970, the minimum dropped to 1%, and the maximum for this specific month reached as high as 71%; 100% of relative humidity has been recorded in seven months in the period 1959 to 1971, figures for three of these months occurring in 1971.

The daily relative humidity varies immensely with temperature, and observations by Sogreah (1968A) showed that in winter the daily maximum occurs at approximately 09 00 a m, and the minimum at approximately 5 00 p.m, while in summer the maximum

TABLE 5.9

Characteristics of Relative Humidity at Riyadh Airport (1965-1971)

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Average Mean	48·58	43·92	41·00	37·33	26·75	14·82	16·76	16·17	17·33	27·33	43·75	45·28
Average Maximum	63·00	67 33	45·33	51·17	88·67	21·50	19·17	28·33	23·50	31·83	54·83	61·33
Average Minimum	28·17	24·77	16·83	22·00	16·50	8·83	9·00	10·00	8·83	13·00	23·67	25·50
Absolute Maximum	100	100	100	100	95	81	68	85	67	98	100	100
Absolute Minimum	8	5	3	1	3	2	4	4	4	6	7	6

Source : Riyadh Airport Station

occurs at approximately 07 00 a m and the minimum at approximately 4 00 p m.

To summarise briefly, the characteristic features of the relative humidity indicate that it is rather low over the whole year, but increases during the rainy season as a result of the westerly and northerly air stream.

CHAPTER SIX

RUN-OFF

6.1 Sources of Run-off

Whilst rainfall can be accepted as almost the only source of fresh water in the earth, the way by which the water accumulates into a single stream-flow is very important for defining the components of run-off. Two multiple purposes are aimed at in this study: the first is to define as far as possible the difference between run-off in a perennial river and an arid-land wadi; the second is to give the general characteristics of one or more flood analyses.

In the run-off in any single river, four components act interdependently to form a stream-flow : (1) direct precipitation; (2) surface run-off; (3) interflow; (4) ground water flow. While it is rather complicated to define the actual volume of each of the components and their distribution in time, they may all contribute a variable amount of water to the stream-flow at a given time and a given point.

In the case of the Wadi Hanifah, all four components hardly ever occur together at any time because of the climatic and ecosystem characteristics. The most important is the overland flow, i.e., the sheet flow of water from the point at which a raindrop reaches the land surface to the point at which it becomes part of the turbulent flow in the channel. Such flow is affected by many factors related to the features of the catchment and the climatic system, both of which will be studied in another section of this chapter.

Direct precipitation over the stream-flow is unlikely to happen except in the finger tips of tributaries where the run-off is formed within the time of rainstorm. Sometimes, however, when the catchment is affected by frontal rainfall of comparatively long duration, the direct precipitation over the various tributaries and dams contributes a negligible proportional volume which is probably consumed by evaporation. The chief effect of direct precipitation can be distinguished indirectly where a channel bed with sand grains has a relatively high soil moisture content, immediately after the occurrence of a storm shower. This causes a decrease in the infiltration capacity on the one hand, and, on the other, helps the run-off or stream-flow to travel a longer distance within the wadi length. The winter season flood, which occurs between November and February, has a comparatively long duration, and consequently may reach the flood-plain of As-Sah'ba and At-Tawdheheyyah at Al-Kharj Plain. In spring, though the density of storm-rain is rather heavy, the flood may have a high peak and travel a short distance, due partly to the high rate of infiltration in the dry channels.

The interflow and base-flow components, which constitute a constant flow, are not available during the whole year. This is due to high soil deficit, which is caused by the high potential evaporation and small amount of rainfall. Thus, when the flood occurs, the depth of the underground water in the alluvium channel is far below the bed surface of the channel. Instead of water seeping to the stream during a flood, infiltration and percolation will take place. The only exceptional case is the seepage flow originating from the impound dams to the downward section of the stream, which is totally dependent on the flood reserves. Equally, during a wet year when floods occur frequently in a short period, for example, two weeks, the date gardens on the silt terrace of the wadi, which are normally irrigated by flood when this is possible, may also contribute a small portion of seepage flow.

Thus the stream-flow of the Wadi Hanifah is composed primarily from the overland flow contributed by the seasonal rainfall in the shape of temporary floods.

6.2 Factors Affecting the Distribution of Run-off in Time

The flood hydrograph of the Wadi Hanifah is controlled by many factors, some permanent and others transient. In any stream-flow the inter-relation of such factors seems to be common. In the case of the Wadi Hanifah, some factors are more dominant than others, as a result of their individual type. Establishing quantitative relations between the flood and those factors would be invaluable, not only for the wadi under study, but also for all wadis of central and northern Saudi Arabia. Such a study needs substantial investigation and long observation at precise locations, something which is not available at the present time. Such factors will, however, be discussed on the grounds of their importance for the flood in order to increase our understanding of the interaction between physical and human systems.

The factors are closely inter-related, and exert a common combined influence. For convenience, they will be classified in three groups. Chief among these is the physical characteristic of the drainage area and the climatic condition prevailing within the catchment. Human interference in altering and modifying the natural conditions is also very important, especially where the trend of water development in the country swings towards computing and controlling the available surface water in order to evaluate the water balance.

6.2.1 Climatic Factors

Climate is probably the most powerful influence on the mass run-off. In a general sense, the balance between water gain and water loss is rather important here. When a comparison is made between the rate of rainfall and evaporation, it is clear that the ratio is as much as 1 to 25. Such a difference is usually modified or reversed on the occurrence of rainfall. Owing to the intensity of the prevailing rainfall, the evaporation rate is smaller than the rainfall in a given place and at a given time.

Thus, if an average 100 mm were distributed all through the year, the run-off might be zero owing to the high rates of evaporation. Even if the water loss and the water gain occur uniformly through a rainy month, the run-off will also be zero. Thus, the reason for the mass run-off, which may be as much as $12 \cdot 80 \times 10^6$ cu m in the Hanifah Dam, is in fact the intensity and duration of the rainfall in a single period, which may sometimes continue for more than one day.

One important point has to be considered here. As the bulk of the run-off occurs through individual storms, close attention should be paid to their sizes, rates of movement, tracks, frequency and distribution over the catchment. As has been mentioned in the chapter on climate, the above factors can be classified in two groups, according to the time of occurrence of the storms, i.e., winter or spring.

In winter, the size of thunderstorms is comparatively large, their density is rather high, and the rate of movement is relatively slow. Consequently, rain tends to cover the whole catchment, allowing a massive run-off to occur at one time.

Though the intensity of rainfall in spring is rather high, rainfall from one single storm occurs in a narrow belt unless successive thunder-showers fall within a short period. Afternoon rainfall in April or May falling on an isolated patch with a relatively high temperature may be lost by evaporation and infiltration before it accumulates in the stream.

The relationship between the wadi slope on one side, and the intensity, duration and movement of the rain-storm on the other, is very important in terms of the peak of flood. Taking the upper sub-catchment, for instance, which was observed at Al-Jubailah, the three major tributaries flowing from west to east, i.e., Al-Khomrah, Al-Hisyan and the wadi proper, join the main stream at roughly the same time, due to the track of the storms, which usually hit the sub-catchment from north-west to south-east. When a rainy-run occurs on the sub-catchment during a previous stream-flow, the peak following the rainfall occurs rapidly and intensely.

6.2.2 Catchment Characteristics

Though precipitation is the only source of run-off in the wadi, the Basin area, including the shape, size and drainage network of the catchment, defines the dimension and magnitude of the flood hydrograph. Infiltration is a rather important factor, since the ground water level always lies beneath the surface of the channel.

Probably the most influential factor is the shape of the catchment area, and its size and slope. In this respect the wadi catchment can be sub-divided into three parts (Fig 6.1):-

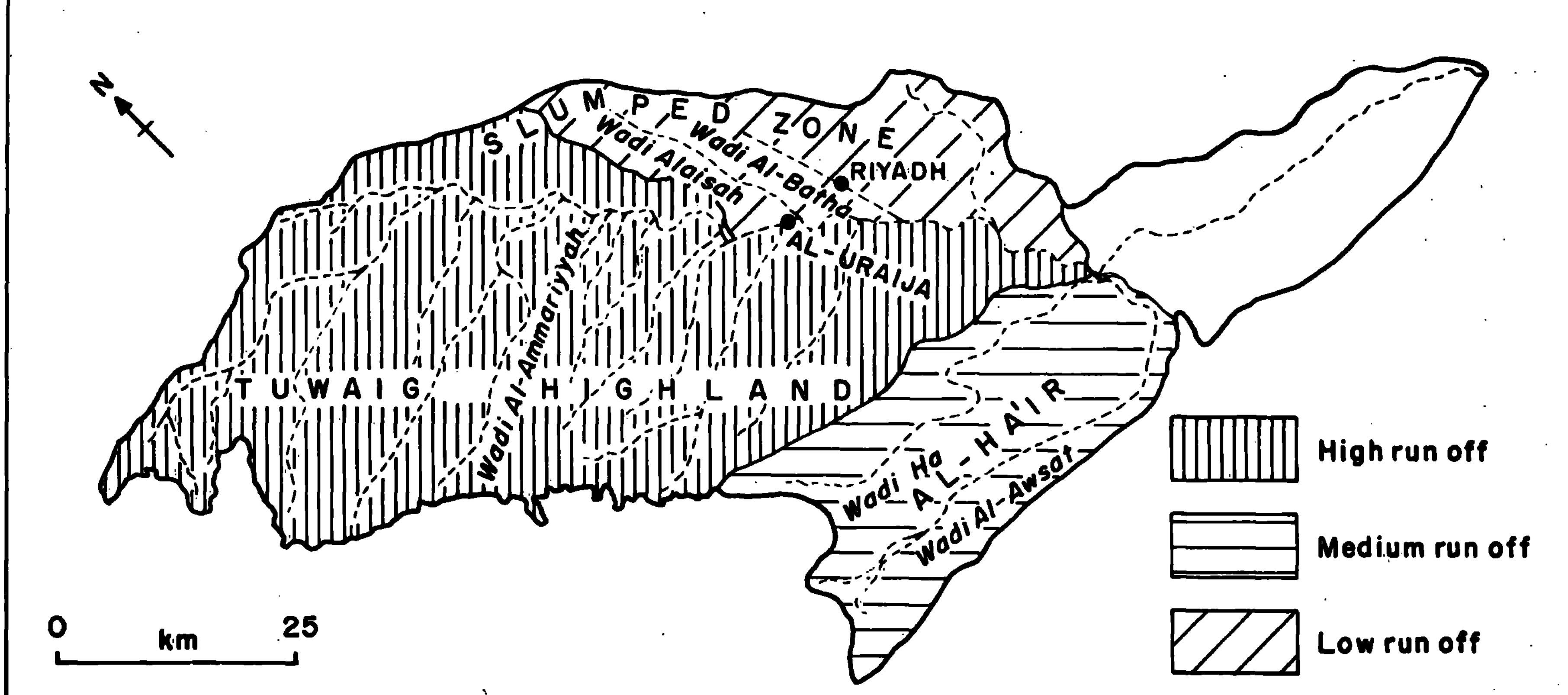
(a) The Sub-Catchment of Tuwaig Highland

An elevation at the water head of the tributaries of more than 900 m above sea level slopes down to an elevation of between 700 and 650 m near their mouths in the main wadi. The proportional loss of water by infiltration is consequently small, and the velocity of the water is also rather high, due to the rocky-type slope, which reduces the influence of evaporation before the water joins the wadi proper. Furthermore, this area of comparatively high elevation enjoys a higher rainfall than that enjoyed by the rest of the basin.

The drainage network of this sub-catchment seems to render it well-drained. No attempt has been made to establish the relationship between the density of the network and the trunk. However, the latest observations of Sogreah (1968A) and the Ministry of Agriculture and Water (1973) show that a substantial volume of the overall run-off of the wadi was drained from this part. For example, in November 1968, Sogreah recorded an observation of the Wadi Al-Ammariyyah, which shows that 3×10^6 cu m of flood had been drained. Though this wadi is the largest tributary within the area, a number of tributaries can, presumably, contribute between $0{\cdot}5 \times 10^6$ and 2×10^6 cu m in a single flood.

While tributaries flow in a rather steep channel from the highland of Tuwaig to the channel of the wadi proper, the latter tends to be more horizontal. Although a difference of gradient is noticed in one or two sections, the extensive land use has led to artificial channels, cultivation

Fig 6·1 HANIFAH SUB-CATCHMENTS IN TERMS OF RUN OFF



techniques and dams, and has modified the original characteristics of the channel.

(b) The Sub-Catchment of Al-Ha'ir

The Al-Ha'ir area appears to have a different type of drainage owing to the relatively low elevation. As has been described in Chapter Four, Physiography, this area lies in the graben and fault belt which crosses the Wadi Hanifah basin. Accordingly, the area has only two major tributaries, i.e., Wadi Ha and Wadi Al-Awsat. The two tributaries drain a substantial amount of their flow from short sub-tributaries which descend from the right and left bank cliffs of their channels.

Owing to the protrusion of the Al-Ha'ir region into the Dhruma Plain to the west of the Tuwaig sub-catchment, the water head sometimes lies in the track of clouds which cross the Dhruma Plain. Conversely, while the sub-catchment of the Tuwaig highland may lie in the track of a particular cloud, this may not pass over the water head of the Al-Ha'ir sub-catchment.

While the tributaries of both wadis, i.e., Ha and Al-Awsat, are steep towards the main channel, the latter has a smooth slope, particularly in the upper heads. This, in fact, provided an ancient track across the Tuwaig Mountain.

The effect of such physical features upon flood is that the two tributaries have long narrow drainage. Both join the Wadi Hanifah proper near Al-Ha'ir village. Owing to their location, which is more than 80 km from the water head of the wadi proper, they supply their flood earlier than the wadi proper, which takes approximately three to four hours before it reaches the Al-Ha'ir area. Thus, if a long observation of flood hydrograph is taken immediately downstream of the Al-Ha'ir area, two peaks will be recorded, one caused by the Al-Ha'ir drainage and the other by the Tuwaig highland sub-catchments through the wadi proper.

(c) Sub-Catchment of Slumped Zone

This sub-catchment is the drainage area of the left bank tributaries of the Wadi Hanifah, in the area between the Wadi Hanifah Dam and Al-Ha'ir. As previously mentioned in the chapters on Physiography and Geology, this area lies largely within the Arab Formation. Despite the fact that the geological series of the central Arabian formation slopes eastward, the existence of small hills in the area creates a poor drainage area flowing to the main channel of the wadi proper. The main tributaries are the Wadi Alaisan and the Wadi Al-Bat'ha. The remaining tributaries are very short and shallow, with an approximate length of between 1 and 5 km. Their effect on the volume and magnitude of the flood in the wadi proper seems to be reasonable when the wadi proper is already flowing; otherwise, their volume of flood may be lost in the sandy channel of the wadi by high infiltration.

The Wadi Al-Bat'ha was connected with the construction of Riyadh City. Its length and subsequently its capacity were reasonable for the old Riyadh, which was estimated to have something like 17,000 inhabitants at the end of the nineteenth century (Abul Ela, 1965A). Nowadays, a large area of its catchment has been lost through the expansion of the city. However, although the wadi channel was modified and converted into a flood sewer for the city centre, the wadi may still flow when substantial rain continues in the remaining drainage to the north of the

Airport.

The Wadi Alaisan has similar physiographical features to the Wadi Al-Bat'ha; its length and size do not allow a large volume of run-off to be drained towards the main wadi. Additionally, it crosses a rather extensive cultivated area before it joins the wadi proper immediately downstream of Al-Uraija village, to the west of the capital city. This cultivated land reduces its capacity due to the diversion of water through artificial channels towards the palm groves.

6.2.3 Land Use

The term "land use" is defined here to mean the impact of human activities in changing the course, volume or velocity of the flood. While the natural phenomena, for example, climate and the physiographical features of the drainage, established the limit of the flood in the wadi, man, on the other hand, started modifying the stream-flow in order to practise cultivation and to protect himself and his environment from damage.

Although the connection between earlier settlements and the wadi basin is not relevant here, a quick look at the wadi before and after the 1950's can, indeed, explain the relationship of two types of human activity to the flood in general. Prior to the 1950's, the wadi had a rural function, limited by the water available in the form of both flood and ground water. That function has been modified by the explosive growth of Riyadh from the 1950's up to the present time. Thus, the urban area has extended in each direction to obstruct some of the old drainage areas and tributaries. Increased urban demand caused the Wadi Hanifah to be drawn on as the first new source of municipal supply. Because of the shortage of water in the alluvium aquifer, the construction of dams started as early as 1959 in the wadi proper, and in the Wadi Liban and Wadi Nimar. Additionally, with Riyadh being the capital city, new roads were built linking the city to the rural area, and these had to be paved; a new bridge and spill-over road consequently caused the diversion of some tributaries to minimise the number of bridges.

For the sake of simplicity, the influence of man over the mass run-off will be classified under three headings:-

(a) Agricultural Techniques;

(b) Urbanisation;

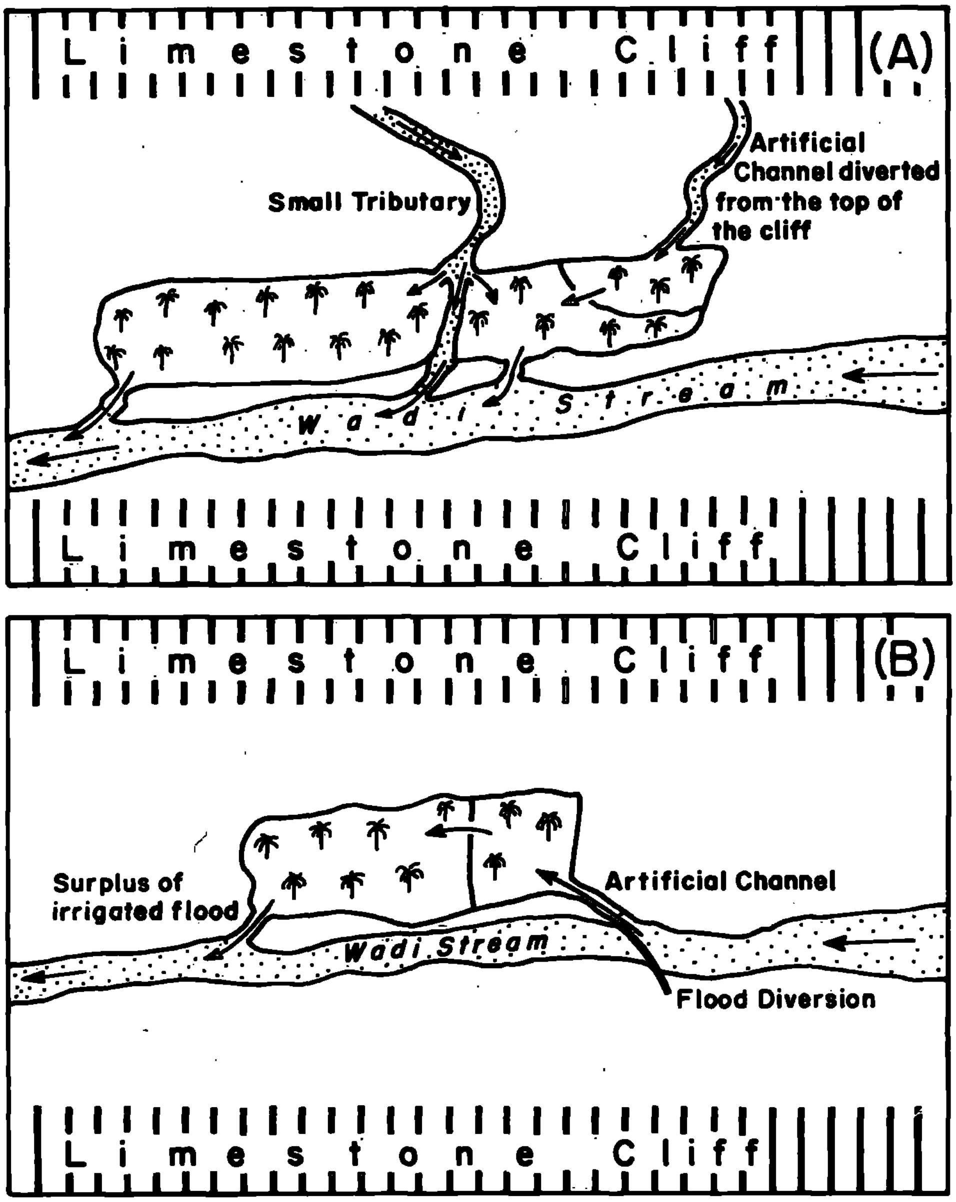
(c) Hydraulic Structures.

(a) Agricultural Techniques

Diversion of flood water started as early as the start of culitvation in the Wadi Hanifah. One prime factor for cultivated land in the wadi is the use by irrigation of flood water whenever possible. However, the elevation of the terrace in some localities is too high above the channel surface for the terrace to be reached by the stream-flow in a moderate flood. On the other hand, a powerful flood is so damaging that those cultivated terraces had to be protected by stone wall barriers. Thus, special techniques were applied in different localities along the length of the wadi.

These techniques were generally of two types. Firstly, in the case of a cultivated terrace adjacent to a small tributary (Fig 6.2A), the flood was diverted in such a way that surplus water was returned to the channel of the wadi. Secondly, in an area where there was no trib-

Fig 6·2 DIAGRAM ILLUSTRATING AGRICULTURAL TECHNIQUES TO UTILIZE FLOOD FOR IRRIGATION



utary, a small dyke with an approximate height of 1 m was built across the width of the wadi before the rainy season (fig 6.2B). Such a barrier raises the surface of the flood in the main channel, so that the flood reaches the area which is to be irrigated.

It is not possible to evaluate the quantity of flood which is used for irrigation; nor is it possible to give the ratio of flood used in this way to mass run-off. However, the statistics of the Ministry of Agriculture and Water (1964) showed that the cultivated area in the wadi was in the order of 3,262·7 hectares. The bulk of this area was so sited that it had its share of the flood water.

While such techniques reduce the magnitude of the flood in the wadi, it is equally true that the flood peak is also affected. The different artificial channels and diversions inevitably reduce the crest of the flood hydrograph and result in a longer duration of the stream flow.

(b) Urbanisation

Unlike the agricultural techniques which affect almost one half of the wadi length, the influence of urbanisation is limited to the expanded area of the capital city.

The expansion of the city has passed through a number of historical stages; the city was originally constructed in the basin of the Wadi Al-Bat'ha, whence it took the name of Al-Riyadh - gardens in Arabic - though a number of historians (such as Yakout El-Hamawey in the thirteenth century) mention its original name as Khadhra Hajr, or alternatively Hajr.* It is quite safe to say that until the outset of the twentieth

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* The name Hajr is written is Arabic as حَجْر

century Riyadh could be classified as a small village. In 1917, the area of the city was estimated to be about 100 acres (Philby, 1922). When it became the capital of a new state (Saudi Arabia) in the first half of the twentieth century, it acquired the ability to attract immigrants from all over the country, in addition to the newcomers from abroad who helped in the development of the growing town.

Thus, two events can be considered as the starting points of the expansion : firstly, the movement of the late King Abdulaziz from the old city to Al-Murabba's Palace, 1·5 km to the north of the old city centre in 1938; secondly, the construction of the Riyadh-Dammam Railway in 1951, coupled with the transferring of the government offices from Jidda to Riyadh in 1957. Abul Ela (1965A) estimated that the kernel expansion of 1938 covered an area nine times as great as that of the old walled city, i.e., 3·5 km from north to south, and 2·6 km from east to west. He estimated also that the city extended 12 km from north to south and 8 km from east to west in the 1960's. Today, the expansion of the city has become very rapid, especially near the highways which connect the city with the remainder of the country.

While the city was, until 1950, only concentrated around the Al-Bat'ha tributary, at the present time the expansion covers almost all the Al-Bat'ha Basin and some of the area around the lower part of the Wadi Alaisan tributary. Previously the Wadi Hanifah proper was the limit of expansion towards the west. In the 1970's, the development of the Ash-Shafa area beside the Riyadh-Taif Highway has caused development to the west of the channel of the wadi proper, paving the way for further extension on the eastern slope of the Tuwaig mountain. Thus, according to the aerial photographs of the Aerial Survey Department of the Ministry of Petroleum and Mineral Resources (December, 1967), together with a fresh check made by the author in February and March 1974, the city now extends about 11km from the city centre, As-Safat, to the north, which almost equals the distance between the latter and Ad-Dir'iyyah village. The extension from the city centre to the Ash-Shafa area along the Riyadh-Taif Highway covers about 8 km.

The city is expected to continue to grow at about the same rate and to have expanded by the year 2000, particularly to the north into the Wadi Alaisan Basin and to the east. According to the Consult Limited firm which established the Sanitary Sewerage Master Plan of the city (1971), the city will stretch 24 km from north to south and 11 km from east to west, with a surface area of about 291 sq km.

The effect of such a sudden and vast expansion of the city upon the run-off and the flood in the Wadi Hanifah differs, in fact, from the effect of a similar development in a humid area. In the latter case, where the water is disposed of through drainage systems, a rapid and marked build-up of surface run-off is likely to occur immediately below a large urban area (Ward, 1967). In the Wadi Hanifah, the effect is more complicated. This complexity stems from the fact that the city suffers from the lack of storm sewage systems.

Before the recent explosive expansion, the building area of the city was sited near the Wadi Al-Bat'ha and the surrounding palm groves. Such a site helped the urban run-off to disperse through the surface ground of the road towards the stream.

Nowadays, the linkage of the old city by new paved roads with the modern building area on the outskirts has created a problem. The old narrow lanes, which lack storm sewage, constitute an area of non-existent or poor drainage, bounded by the high elevated paved road Consequently, such sewage, after torrential rain, either disperses into nearby old covered hand-dug wells, or accumulates in ponds in the middle of the roads and remains there for some time until it is lost by evaporation and percolation.

In the case of some of the major paved streets which slope towards the artificial channel of the Wadi Al-Bat'ha, a sewage drainage network has been constructed. The proportional quantity of such discharge is probably insignificant at the moment, in comparison with the overall run-off in the city.

The bulk of the run-off in the city vanishes by both evaporation and infiltration. The latter, which is more important in terms of ground-water recharge, takes place partly through the filling of the old hand-dug wells which were distributed all over the city. This factor, in addition to the domestic sewage disposal which also infiltrates continuously, gives rise to the local underground water (see Chapter 8 on Jubaila Aquifer).

Owing to the problem of water shortage in the Wadi Hanifah region, the overall run-off in the city - excluding the domestic sewage disposal - may contribute a considerable amount of surface water. Such an expectation will not, however, be fulfilled unless the storm sewerage system is carefully designed and diverted either to the main wadi stream or to be used for irrigation purposes. By this means, the negative effect upon the surface run-off of the Wadi Al-Bat'ha and Wadi Alaisan could be avoided. Furthermore, the impermeable surfaces of the city, paved roads, house roofs, etc., will enable a substantial proportion of rainfall to escape infiltration and evaporation. Thus the mass run-off of the city will probably be greater than the Wadi Alaisan and Wadi Al-Bat'ha together.

The previous hypothesis is based on two facts. Firstly the surface area of the town will be larger than the catchment of all the Wadis Harigah, Ghubairah, Sofar, Mahdiyyah and Wubair.
Also, the spatial area of the city, in almost two decades, is expected to be as large as 50% of the largest tributary, i.e., the Wadi Al-Ammariyyah. Secondly, the drainage system of the city follows roughly the same slope as the Wadi Al-Bat'ha, which slopes gradually from north to south, joining the wadi proper at the south end of the greater Riyadh.

(c) Hydraulic Structures

This term here means primarily the dams in the wadi proper and the main tributaries. The wadi region contains seven dams, plus two more under construction. All dams are built in the area between Al-Uyaynah village in the upper reach and Al-Ha'ir.

Prior to 1958, the Wadi Hanifah flowed along its length, without any obstacles apart from those arising from the practice of agriculture, mainly in the middle part. Thus, it was not uncommon for the flood to reach the Al-Kharj area, especially when overall run-off occurred in the whole catchment.

The growth of the city of Riyadh, coupled with a continuous increase in the standard of living in the city, made it necessary to establish a municipal water network. The alluvium aquifer was traditionally known as a comparatively major water reserve, and exploration and tapping was carried out near Ergah village and the Wadi Nimar, in the Al-Batin area, west of Riaydh, and later in the Al-Ha'ir area. At that stage, it was felt that the alluvium underground water was unable to meet the increasing demands of the city. Moreover, the traditional hand-dug wells were being deepened to increase supply. When the Minjur aquifer was discovered and tapped in 1956, a substantial volume of water was found, but its quality was not as good as that of the alluvium aquifer, in the Wadis Nimar and Al-Ha'ir. Thus the alluvium aquifer continued to be exploited to supply both the city and agricultural demand.

During the same period, the fear of water exploitation in the aquifer was also present. Accordingly, the idea of constructing sub-surface and surface dams along the wadi and main tributaries was recommended by most experts. Aramco (1948), in its investigation on the water supply for Riyadh, recommended constructing a series of underground dams along the wadi and low surface dams in main tributaries; this suggestion was followed immediately by engineering studies by the International Bechtel Company between 1948 and 1951. In 1950, J F Brown, Director of the United States Geological Survey Mission to Saudi Arabia, stressed the need to construct groundwater dams along the wadi, as had been suggested by Aramco. But, after a study of the economic feasibility of underground dams in the wadi, International Bechtel (1951) concluded that the saving of water involved would not justify the cost of construction. Instead, they recommended the construction of two surface check dams in the Wadi Liban and in the main wadi, i.e., Liban Dam and Hanifah Dam. The arguments for and against building dams were mentioned in almost every investigation for Riyadh water supply, including those undertaken by the Pakistan Technical Survey Mission to Saudi Arabia in 1954, and the Raif M Parsons Engineering Company in 1958.

Following these investigations, the Riyadh Municipality started the construction of two dams, one in the Wadi Nimar tributary and the other in the Wadi Liban tributary. Both were completed in 1959. The construction of Hanifah Dam was also completed in 1960 (Ministry of Agriculture and Water, 1971). These hydraulic structures having been completed, the wadi was then left for agricultural purposes, owing to the development of the Minjur Aquifer, which supplied water to the city.

Another epoch of construction started in 1968, with the building of three small dams in the Wadis Sofar, Ghubairah and Harigah, near Ad-Dir'iyyah village. The construction of two dams in the Wadi Hanifah proper was proposed, the Ha'ir Dam was to be located 2·5 km upstream of the Water Treatment Plant at Al-Ha'ir and the Dir'iyyah Dam between the mouth of the Wadi Al-Ammariyyah and Ad-Dir'iyyah village (Shaikh, 1972). Details of their capacities are not available, but it is assumed that each one will hold between 1·5 and 2 million cu m of water.

Though all the dams are constructed for re-charging the alluvium aquifer, they influence all the mass floods and the hydrographic peaks. All have been built on the area with effective run-off and comparatively intensive agriculture. The Ad-Dir'iyyah Dam will obstruct any small volume of stream-flow due to occur from the upper reach of the wadi proper or from the Wadi Al-Ammariyyah. The same result is likely to be caused by the small dams on the Sofar, Ghubairah and Harigah Wadis. The Hanifah Dam will be supplied mainly by the Wadis Mahdiyyah and Wubair immediately upstream, and in addition by the surplus flood overspill from the Ad-Dir'iyyah Dam. The Ha'ir Dam will hold the flow of the slumped zone sub-catchment in addition to short tributaries flowing from the triangle to the east, bounded by the Riyadh-Taif Highway in the west, the watershed of the Wadi Ha in the south and the main wadi in the east.

When the construction of Ad- Dir'iyyah Dam and Ha'ir Dam is finished, the Wadi Hanifah will be unable to reach the Al-Kharj Plain unless a substantial and continuous run-off occurs. In other words, even if the flood passes the Al-Ha'ir area, the wide and gradual slope of the Wadi Hanifah channel further downstream will help the flood to be lost by infiltration and evaporation. However, the areas which are still free of any flood restriction are the area upstream of Al-Uyaynah village, and Al-Ha'ir subcatchment.

If any run-off occurs in the whole catchment of the Wadi, two flood peaks presumably pass the Al-Ha'ir area. The first one results from the Wadis Ha and Al-Awsat which meet with the wadi proper almost together in one short section of its course. The second occurs as a result of the spillway flood leaving the other dams in the middle course.

The volume cpacity of all the existing dams is about $19 \cdot 87 \times 10^6$ cu m. Though this quantity looks rather small in terms of overall flow, the distance between them, which has a high infiltration rate, might force any small portion of flood passing any individual dam to be lost by infiltration. Thus, unless a substantial flood occurs, the wadi course south of Riyadh City will have a minimum flow (Plate 6.1).

6.3 Flood Observations

The climatic regime and the size of the wadi catchment mostly decide the magnitude of the flood. In other words, the flood occurs for a comparable time to the occurrence of local rainfall.

In dealing with the flood characteristics of the Wadi Hanifah, as well as other wadis in the Tuwaig mountain, the important point is to define the dimension and the volume of the surface flow at a given time. The aim of such an investigation is not to avoid a flood tragedy, which is out of the question nowadays owing to human intereference with the flood; it is rather to take advantage of the flood as much as possible in such a way that an accurate estimate of its impact upon the shallow underground water can be taken into account.

Flood observations started as early as human settlements on the wadi; the villages, which have been located on or near the cultivated terrace, were constructed in such a way that damage was, as far as possible, avoided. Such an intention can be seen in flood development and management over the years. Cultivation has been developed, for instance on the silt terrace which could be protected from flooding, even in the wettest years. Within such management, velocity, height and dimension of floods have been given some consideration. Hydraulic structures and human interventions for controlling the flood were sited and adjusted to cope with the flood shape and magnitude.

The investigations which started in the late 1950's and early 1960's were related to the construction of dams and bridges on the wadi proper

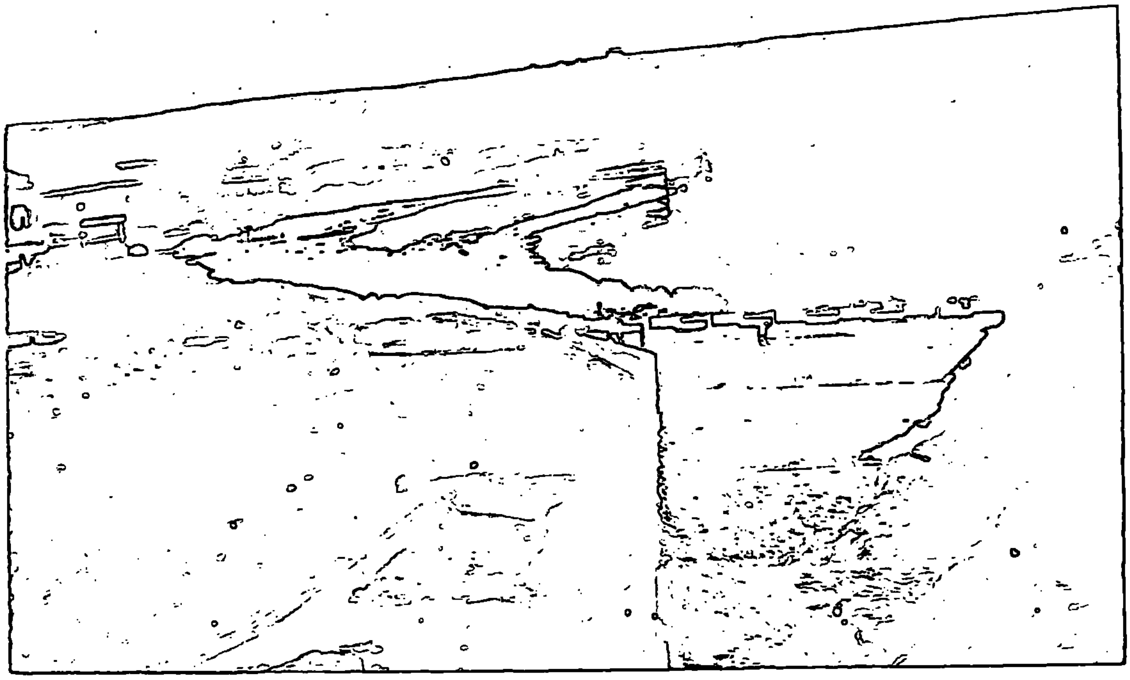
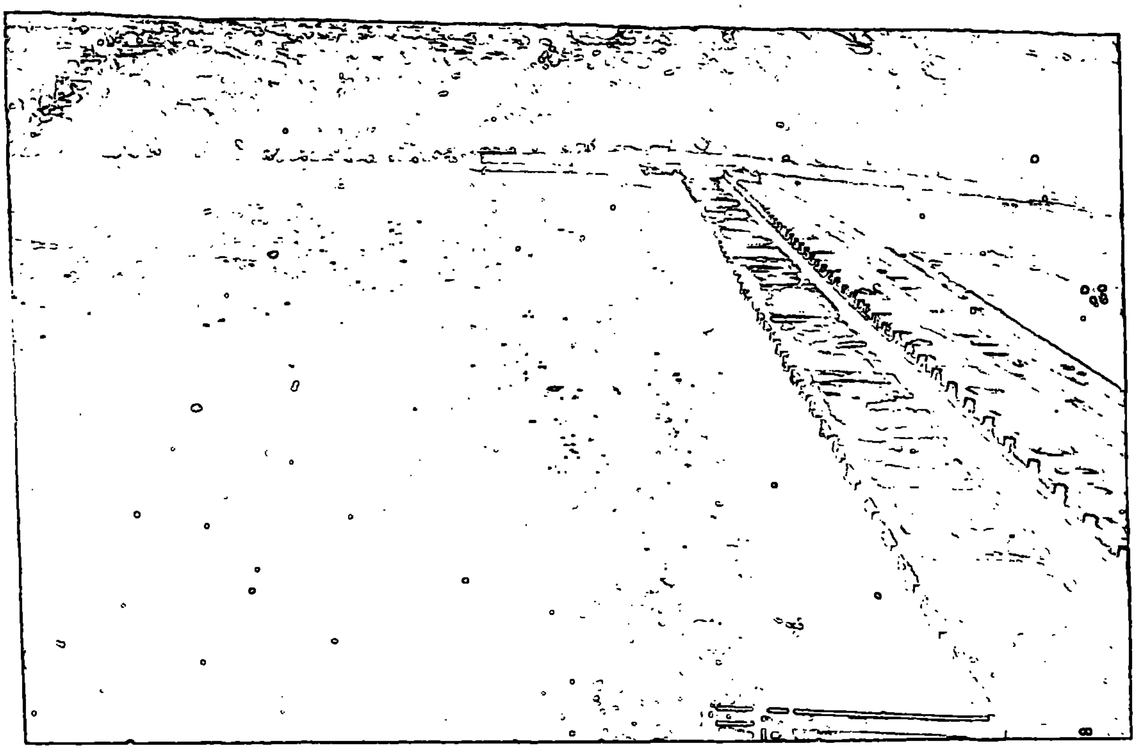


Plate 6.1

The effect of the Nimar Dam (below) on the flow of flood downstream (above)



and the main tributaries. Thus, the necessities of planning led to mathematical estimates of flood behind the dams. Other precise observations were made from 1965 onwards by the Water Resources Division of the Ministry of Agriculture and Water, and also by Sogreah between 1966 and 1968; both sets of observations will be considered in this section. The observations of the former are mainly concerned with the behaviour of the Wadi Hanifah Dam in terms of its water reserve. The latter, in 1967 and 1968, succeeded in recording four flood hydrographs in four sections of the wadi proper, i.e., at Al-Jubailah in the upper reach, Hanifah Dam, Al-Ha'ir and for the surplus of flood which passed Al-Kharj Bridge.

According to the few observations carried out before the building of the most recent hydraulic structures in the wadi, the volume of flood passing through the middle reach is believed to have been larger. In January 1958 a storm lasting for about 40 hours produced about 7×10^6 cu m, as measured at the Al-Badi'ah Bridge to the west of Riyadh City. An estimated flow of about 45×10^6 cu m in 24 hours was also given in another storm occurring on 15th February 1958 (Davis, 1959). Such a relatively substantial flow of the wadi appeared to reach the Al-Ha'ir area where the wadis Al-Awsat and Ha join the main wadi and it descends to the Al-Kharj Plain.

Data collected by the author from the office of the Hydrology Department in Riyadh (Table 6.1) show the irregularities of flood in terms of its occurrence and volume. Within the recorded period (between 1964 and 1972) the total volume of flood passed through the Hanifah Dam was of the order of $55{\cdot}55 \times 10^6$ cu m. Slightly more than

TABLE 6.1

Volume of Flood Passing through the Hanifah Dam (1964-1972)

(Volumes expressed in 10^6 cu m)

Month *	1964/ 1965	1965/ 1966	1966/ 1967	1967/ 1968	1968/ 1969	1969/ 1970	1970/ 1971	1971/ 1972
November	-	2·39	-	4·95	-	-	-	-
December	-	2·30	-	0·64	-	-	-	-
January	-	-	-	0·36	1·48	-	-	0·09
February	-	-	-	9·47	0·04	-	-	-
March	-	-	-	1·45	-	-	6·27	0·29
April	11·23	-	0·10	5·90	-	-		7·14
May	0·03	-	0·06	0·60	-	-	-	0·49
June	-	-	-	0·28**	-	-	-	-
Total	11·26	4·69	0·16	23·65	1·52	-	6·27	8·01

* No flood observed from July to October inclusive.

** This volume is probably the remaining portion of the May flood.

Source : Office of the Hydrology Department of the Ministry of Agriculture and Water, Riyadh (1972)

20% of this volume was recorded in one month - April 1965.

This clearly reveals the nature of the run-off in the Wadi, which is characterised by a high density of rainfall from time to time. It gives a clear idea of the characteristic of the Wadi Hanifah catchment in comparison with other wadis in the Tuwaig mountain. That is to say, whereas the other wadis in the eastern slope of the Tuwaig mountain flow in a west to east direction, their catchments are smaller than that of the Wadi Hanifah, which behaves in its middle reach as a collector of major tributaries with a considerable catchment surface, for example the Wadi Al-Ammariyyah.

Owing to the climatic regime of the area and the physiological characteristics of the catchment, the overall flow of the Wadi Hanifah cannot be deduced from one given point. In other words, one sub-catchment can contribute stream-flow, while others may be dry at the same time. If the observation is carried out at the lower end, for example Al-Kharj Bridge, the result will be meaningless in terms of the stream flow in the upper and middle reach owing to the high rate of infiltration between Al-Uyaynah in the upper reach and Al-Kharj Bridge.

Accordingly, the observation of the volumes of flood accumulated in the whole length of the wadi (Table 6.2), revealed that the volumes ranged between $11{\cdot}7$ m 10^{6} cu m and $24{\cdot}3 \times 10^{6}$ cu m. An average of 96% of the flood was lost by infiltration and evaporation. The remaining portion found its way through Al-Kharj Bridge.

Due to the irregularity in the temporal and spatial distribution of rainfall, the volume of flood in various sections of the wadi differs distinctly. Thus, the data for the section between Al-Jubailah and Hanifah

TABLE 6.2

Observation of Four Floods in the Wadi Hanifah

(Volumes expressed in 10^6 cu m)

Description	April 1967	November 1967	February 1968	April 1968	Average
Flood passing beyond Al-Jubailah	0·30	8·30	8·00	4·00	5·15
Lateral inflow between Al-Jubailah and Hanifah Dam	1·80	6·40	12·50	7·50	7·08
Loss by infiltration and evaporation	2·00	8·90	11·30	3·70	6·48
Flood impounded at Hanifah Dam	0·10	1·40	0·90	1·30	0·93
Volume of flood leaving Hanifah Dam	-	4·40	8·40	6·50	4·83
Lateral inflow between Hanifah Dam and Al-Ha'ir	9·60	2·00	3·20	12·80	6·90
Loss by infiltration and evaporation	6·10	4·90	8·20	12·30	7·88
Volume of flood flowing beyond Al-Ha'ir towards Al-Kharj Bridge	3·50	1·50	3·40	7·00	3·85
Loss by infiltration and evaporation	2·74	1·50	3·20	5·15	3·15
Total volume of flood accumulated in the Wadi	11·70	16·70	23·80	24·30	19·13
Total volume infiltrated and evaporated (between Al-Jubailah and Al-Kharj Bridge*)	10·94	16·70	23·60	22·45	18·42
Volume of flood which escaped infiltration and evaporation and therefore passed Al-Kharj Bridge	0·76	-	0·20	1·85	0·70

* The volume of flood impounded at Hanifah Dam is included in this figure.

Sources : Sogreah (1968A) and (1968D); Office of the Hydrology Department, Riyadh

Dam are separated from that data for the section between the Hanifah Dam and Al-Ha'ir. The irregularities can be seen in any single flood observation. For instance, in the April flood of 1967, the section between Al-Jubailah and Hanifah Dam contributed only $1 \cdot 8 \times 10^6$ cu m, most of it drained from the tributaries of the Wadis Al-Ammariyyah, Wubair and Al-Mahdeyyah. In the section between Hanifah Dam and Al-Ha'ir, the proportional volume was as high as $9 \cdot 6 \times 10^6$ cu m. The observation of the flood occurring in November of the same year showed that the former section received $6 \cdot 4 \times 10^6$ cu m, while the latter section received only $2 \cdot 0 \times 10^6$ cu m. In such conditions, where the southern sub-catchment has got a substantial inflow, there is a possibility of a rather high proportion of flood passing Al-Ha'ir towards the Al-Kharj Bridge.

In the case of the lower reach (beyond Al-Ha'ir), the proportional volume of flood passing the Al-Kharj Bridge is very small when compared with the volume accumulating in the whole Wadi. In February 1968, the observation of the flood showed that the volume of flood in the Wadi was $23 \cdot 8 \times 10^6$ cu m, and at the Al-Kharj Bridge it was only $0 \cdot 2 \times 10^6$ cu m. In April of the same year, while $24 \cdot 3 \times 10^6$ cu m was recorded in the former, $1 \cdot 85 \times 10^6$ cu m was recorded at the latter. This proportion will eventually decrease when the Al-Ha'ir Dam is constructed. The only flow that will then find its way without any hydraulic obstruction is the flood of Wadis Al-Awsat and Ha, and this is too small to reach the Al-Kharj Plain without any substantial flow through the wadi proper.

It may be concluded that three areas are responsible for the increase in the total inflow in the Wadi. This first is the drainage of the Tuwaig highland between Al-Jubailah and Hanifah Dam. This area contributed about 37% of the total inflow of the Wadi. The second area is the drainage of the Tuwaig highland between Hanifah Dam and Al-Ha'ir, including Al-Ha'ir sub-catchment. Although the flow in this area is obstructed by the dams of Wadi Liban and Wadi Nimar, it contributed about 36% of the total inflow of the Wadi. The third area is the drainage of the Tuwaig highland in the upper part of the Wadi Hanifah, mostly the Wadis Al-Khomrah, Al-Hisyan and the water-head of the Wadi Hanifah proper. The contribution of this area was in the order of about 27% of the total inflow of the wadi. The slumped zone area seems to contribute a very small quantity when compared with the areas of an active run-off in the Tuwaig highland. This has been caused by the lack of rainfall as well as the small drainage of its tributaries.

CHAPTER SEVEN

ALLUVIUM AQUIFER

One of the dominant features of Saudi Arabian history has been the scarcity of water, which has prevented people from efficiently cultivating the land and forced them either to accept the challenge of the environment or to emigrate to better land.

According to the scant evidence concerning the region's past history, the Wadi Hanifah has attracted people from neighbouring areas because of the easy accessibility of its water either in the form of surface flow or of shallow ground water.

Given sufficient rainfall or permanent streams, man is able to practise cultivation and to domesticate animals, but in an area such as the wadi, which is located in a vast desert where nomadism has existed for a very long time, the practice of agriculture through flood control management and the utilisation of underground water has also been pursued since long before the rise of Islam. Unfortunately, little is know of the history of the wadi prior to the time of Islam. Al-Jasir (1966) pointed out that water was abundant in the wadi, and that the region had more water and cultivated land than any neighbouring region. A trace of a past important channel was found at the confluence of the Wadis Hanifah and Al-Bat'ha, which provided the area with sufficient water for human settlement. Another example was Al-Uyaynah village, on the upper reach of the wadi catchment. The name of the village means a "small spring", which still exists. The water came from lateral surface seepage through the left bank of the Wadi Hanifah. From the trace of the spring channel, it was observed by the author in April 1974 that the stream had previously been deeper, and the gorge wider. This might have been caused by a greater or more constant flow in the past. Nowadays, the spring flows during the wet years for almost two months, and dries up for the rest of the year. This is a result of the severe depletion of the subsurface aquifer, possibly linked with a change in the weather.

Up to three decades ago, the water use was devoted mainly to traditional agriculture. When modern pumping equipment was introduced, Wadi Hanifah began to suffer from a water shortage, but because the country was then in the first stage of its development, people and authorities tried to drill new wells and deepened the existing boreholes in the hope of making more ground water available. Ever increasing utilisation of water and a lack of knowledge accentuated the problem.

The surveys and investigations carried out by Aramco and other foreign experts paved the way for a realisation that water was so precious that efforts had to be made, not only to extract and drill for it, but also to conserve it.

Many reports were also presented to the government of Saudi Arabia; most of them explained how to improve the life of the country in general, including water development and management. Priority was given then to investigation and drilling in the Wadi Hanifah, owing to its location near the capital city, at a time when other regions of the country were too isolated and far away to supply water to Riyadh, or even to provide agricultural produce. Gardening was already established in the wadi, where hand-dug wells were in operation; the lowered water levels and the desire for increased production prompted farmers to deepen their wells and install centrifugal pumps, which were usually set up in the old hand-dug wells. By 1948, many of these wells had been abandoned, since the water level had dropped, thus highlighting the problem of water shortage. From then on, an acceleration in discharge from the remaining wells increased the rate of lowering of the water level.

7.1 The Extent and Nature of the Aquifer

The alluvium aquifer extends along the Wadi Hanifah in the Quaternary fill of the main channel. To define the exact extent of the usable area, one must look to certain locations within the Wadi, where the aquifer has already been tested and utilised. These locations extend from Al-Uyaynah village (near Lat 24° 55' N, Long 46° 27' E) downstream to the area of Al-Ha'ir. In addition, the aquifers near the mouths of the tributaries have more or less the same character as the aquifer in the main channel. The area beyond these limits is excluded from this study, since the area upstream from Al-Uyaynah village has no water points by which the aquifer could be tested, and it is doubtful whether it has a major exploitable aquifer. The lower area downstream from Al-Ha'ir area has no importance in terms of exploitable water, because the thickness of the Quaternary fill decreases. There is some scattered cultivation which can be seen from the Riyadh-Al-Kharj road, though the road is, in fact, outside the wadi channel, and this cultivation depends for water on the Sulaiy formation rather than the Wadi alluvium aquifer.

Thus the alluvium aquifer stretches from Al-Uyaynah along the wadi course, where intense cultivation has taken place for more than

1,500 years. The length of the wadi here is about 100km, with an average width of about 500 m. The alluvium deposit in which the aquifer exists is embraced by the channel cliffs, which mostly consist of the Jubaila unit rocks, the difference in elevation between the superficial alluvium bed and the limestone plateau in both banks being of the order of 30 to 40 m in the Al-Ha'ir area and slightly more in the area of Ad-Dir'iyyah and the Wadi Hanifah Dam.

The alluvium, according to a sight test borehole drilled by Sogreah in 1967, appeared to be heterogeneous. It varies from fairly silty fine sand to pebbles about 10 cm in diameter. Nearly two-fifths of the sediment consists of discontinuous lenses of sand and silt, with interbedded deposits of sand and gravel; together this probably forms 50% of the thickness of the Wadi alluvium (McCann, 1959).

Silt deposits in the Wadi Nimar formed impermeable lenses which in turn affected infiltration downward and created small semi-perched aquifers. This phenomenon was detected by observing some shallow wells in the area where the water level is higher than the water level in adjacent wells. The occurrence of ground water can be traced in the underlying permeable sediments of the Wadi alluvium, which consist mainly of fine grained deposits, as well as sands and gravels.

The thickness of the alluvium in general ranges between 60 m near the Hanifah Dam to nearly 30 m in the Al-Ha'ir area. In some places, the thickness decreases markedly as a result of folding in the underlying Jubaila limestone.

However, the limestone, which acts as a base for the alluvium, is in some places water-bearing. In spite of the general opinion that the

Jubaila unit underneath the alluvium is impermeable, it was found by Sogreah in 1966-67 that some wells in the Al-Ha'ir area did, in fact, traverse the alluvium and penetrate the limestone. Because water investigations of these wells were initiated only after the water table had dropped, no attempt has been made to determine the exact amount of water underneath the alluvium. The existing hand-dug wells in the lower part, near Al-Ha'ir, may obtain some water from the fissures and joints of the limestone. In the upper part, near Ad-Dir'iyyah for instance, it is doubtful whether any old hand-dug well reaches the limestone because of the comparatively thick alluvium. However, the amount of water which used to be extracted from the old shallow wells is insignificant, in terms of the total volume of water in the aquifer.

When the transmissibility and the permeability of the aquifer were tested in the Al-Ha'ir area, they were found to vary widely in value from place to place, presumably because of the heterogeneity of the alluvium sediments. The permeability value indeed ranges widely between 4 and 40×10^{-4} m/s (Sogreah, 1968A). As these values have been tested in Al-Ha'ir region only, the results cannot reliably be applied to the aquifer as a whole. Nevertheless, they can be taken as a general basis for future investigation. The movement of the subsurface water is rather difficult to determine at this stage. All one can say is that, owing to the different types of Quaternary deposit, the flow and the hydraulic head or gradient of the ground water is controlled by the deposit. Thus, the silt deposit allows a slow flow, which means that the water in the upper stream may take some time before it reaches the middle and lower reach.

7.2. Boundary Conditions of the Aquifer

In discussing the boundary conditions, the aim is to give a clear idea of three main factors governing the behaviour of the aquifer. It is important to say here that, although the whole wadi will be considered in forming a general picture, the areas which have been tested are the Al-Ha'ir area in the southern part of the wadi, and the exploitable aquifer upstream, both of which have been defined before. The boundary conditions are decided by three main factors:-

Water table and water table variation;

Recharge;

Discharge.

7.2.1 Water Table and Water Table Variations

The availability of water combined with the cultivable silt terrace determines the density and distribution of human settlements within the wadi. Consequently, the location and size of settlements has locally affected the water table. Unfortunately, before 1947 no investigation was undertaken which would provide a basis for estimating the water level. To supply this deficiency, more than 25 interviews were held with elderly ex-farmers who were still living in their villages and who had observed the water level during their lives. These interviews took place between 20th and 26th January 1974, at different villages throughout the whole length of the utilised aquifer, particularly at Al-Uyaynah, Ad-Dir'iyyah, Riyadh City and Al-Ha'ir. In addition, two interviews were carried out in Al-Ammariyyah village.

According to local people, the water level variations were controlled by the flood.

When the wadi channels were flooded more than three times during the year, the water level would rise distinctly; it probably reached about 5 m from the surface in the section between Al-Jubailah in the upper stream and somewhere between Manfouhah village and Al-Ha'ir area. At Al-Ha'ir, the water table rose right to the surface following a succession of flood flows. The villages could not recall the dates of such rises, though it was suggested that they probably happened every 13 years at most. The decline of the water level used to occur slowly through the whole hydraulic year. The period between July and September was claimed to be the worst period, when the water level reached its lowest point. To establish the lowest limit of the water table before recent development is not difficult, for the old hand-dug wells penetrated to the deepest level reached by the water. The total depth found between Al-Uyaynah and Manfouhah does not exceed 30 m. Different depths were reached at different times, in consequence of the lowering of the water during drought years. The approximate depth of all wells is about 12 and 20 m. According to the earliest report submitted by Aramco (1948), the water level stood between 5 and 9 m below the surface before 1935. This estimate is probably accurate, since the level conforms to that at present in some areas which have not been heavily affected by pumping.

Between 1938 and 1948, the change in the level began in Riyadh City, along the Wadi Al-Bat'ha, which traverses the city from north to south beside the Airport Street and Al-Bat'ha Street. Because this wadi is conveniently adjacent to the old city, a number of boreholes were drilled, particularly near Al-Thumairi Gate, at the junction of King Faisal Street and King Abdulaziz Street in the capital city. These showed that the water level had dropped to 10 m in a period of some eight years. It was realised then that most boreholes had dried up and the Wadi Al-Bat'ha was eventually abandoned. The water level in the Wadi Hanifah proper at this time was probably not largely affected, particularly in the reach upstream and downstream of Manfouhah village and Al-Batin to the west of Riyadh City.

When the first record was started by Aramco in March 1948, the water in the whole length of the Wadi proper was more or less at the same level, except in the far extremities up and downstream (Fig 7. 1). Al-Uyaynah, Al-Jubailah and Wadi Nimar sections showed a drop of a few metres beneath the general level of the downstream area. The reason was probably the rapid drawing of the water in these cultivated areas, combined with the subsurface flow toward the lowest parts downstream. Towards the southern end of the Al-Ha'ir area, where the two main tributaries, the Wadi Ha and the Wadi Al-Buayja, join the main Wadi, the water was a few metres beneath ground level. Here the alluvial deposit is thicker than in the area immediately upstream.

The second record of the water level was again compiled by Aramco in 1950. The measurements showed a semi-depression in the central part between Ad-Dir'iyyah and Manfouhah. An average drop of 3 m below the previous level was recorded, but in some wells along this section a drop of 7 m was detected. During the period March to June 1951, the decrease in the water level was claimed by International Bechtel (1951) to equal 0·04 m per week. At the same time, a rise of

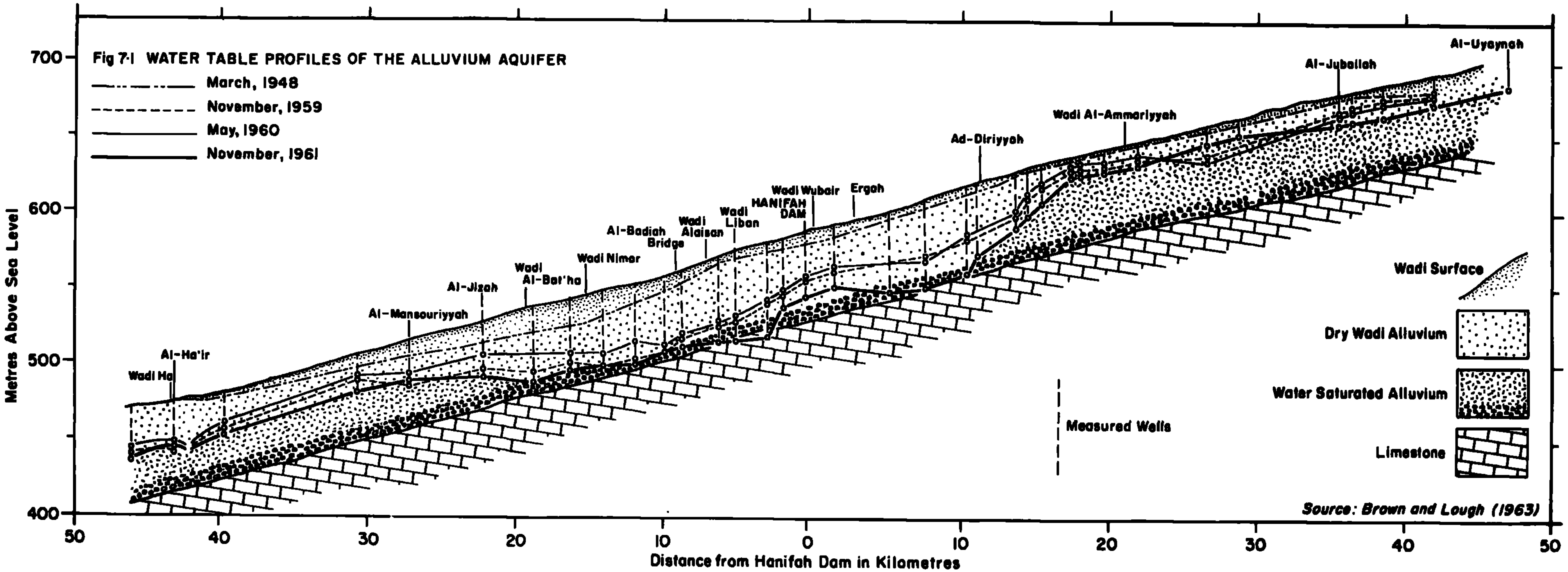


Fig 7·1 WATER TABLE PROFILES OF THE ALLUVIUM AQUIFER

Source: Brown and Lough (1963)

nearly 1·52 m is also recorded as a result of some 12 mm of rainfall on 9th and 10th March. After 1951, a deterioration west of Riyadh City was observed, when boreholes were drilled for domestic water supply at Al-Batin and As-Suwaidi, between the Wadi Nimar and the Wadi Liban; a decline of 16 m was recorded in the lower reach of the Wadi Nimar (Davis, 1959A). According to Wilson (1953), the cumulative decline at that time was approximately 25 m. By 1953, the semi-depression west of Riyadh had extended between Hanifah Dam and Manfouhah village. The water level within this area had dropped to 21·5 m (Davis, 1959B) below surface. Needless to say, this fall was caused by the relatively heavy pumping to supply the city's demands. In addition, the decline of the water level in the adjacent limestone, due to the drilling of boreholes in the city, may have aggravated the drop of the level in the wadi channel. The upper reach above the Wadi Wubair is believed to have been affected by the new mechanical equipment which was being operated in the old wells and new drilled boreholes. Unfortunately, no measurements were recorded.

The lower reach at Al-Ha'ir appears to have had a partial flow until 1956, when new boreholes were drilled to supply the capital city. Then the level started to drop every year. In 1959 the water level had fallen to about 30 m below surface in the exploited wells, while the average level stood at 20 m from the surface.

When the new projects began in Al-Ha'ir and the first of the Minjur water was extracted, the record of the water level in the Wadi Hanifah appears to have ceased. This was a consequence of the search for a new source of water to supply the growing city of Riyadh, and the search had, in turn, resulted from the measurements taken in the alluvial channel of the Wadi Hanifah. The Water Authority did not continue measuring the previously recorded locations.

During the dry season of 1957, a measurement taken at Al-Badi'ah, west of Riyadh City, showed that the water level had fallen to a depth of 35 m below surface. Twelve metres were made up again by the substantial inflow accumulated in the Wadi channel following 57·2 mm of rainfall during January 1958. However, the accumulation was found to have been depleted once more when the well was measured the following September. Moreover, the water level had dropped to a record depth of 42 m below surface. While in the upper reach the water resources seemed to have been less depleted, the rise in the water level, resulting from the flood of January 1958 in Ad-Dir'iyyah, was reported to be only 6 m, and probably less in the Al-Uyaynah area. An overall measurement of the water level from Al-Uyaynah to the site of the Hanifah Dam was recorded at the end of the dry season of 1958 (McCann, 1959); the results showed that the depth of the water in Al-Uyaynah was about 15 m below surface, and in Al-Jubailah 10 m, while Al-Mughaider, at the confluence of the Wadi Al-Ammariyyah, had a depth of 12 m. From the upper stream of Ad-Dir'iyyah to the lower reaches the level declined from 12 to 30 m. Finally, 35 m were recorded at the village of Ergah and 30 m at the Hanifah Dam. Downstream of the Hanifah Dam, the gradient of the water level abruptly increased to the confluence of the Wadi Nimar, where the water level reached the basal level of the alluvium. Another measurement of the area, taken downstream from the Hanifah Dam, at the same period, indicated that the water table between Al-Badi'ah Bridge and the Wadi Nimar was at its deepest level. The depth of the water was about

45 m beneath the ground.

Thus, a depression has developed over the years, over 45 m along the main wadi channel (Fig 7. 1). The depression very clearly illustrates the heavy pumping that has gone on in the area to supply Riyadh and the local farmers. The most affected sections within the depression are the Ergah section and Al-Batin, west of the capital city. Here, new drilling has taken place since the first warning of the water shortage. The measurements of the Ministry of Agriculture and Water in the wet season of 1961 and 1962 showed that the depression is far from achieving a replenishment balance, except in the areas where impounding dams have been constructed; though such dams make infiltration difficult, they undoubtedly benefit the surrounding areas. The major cause of the drop in the water table is certainly the use of modern mechanical equipment. According to the statistics of the Ministry of Agriculture and Water (1964), the region of the Wadi Hanifah has 679 operating wells. 244 of these are drilled wells, and they are concentrated mainly in the area between Ergah village and Al-Ha'ir, mostly on a 20km stretch between Ergah and Manfouhah. The rest of the operating wells are hand dug, and now operated by turbine-driven pumps. Such a classification of the wells, as either drilled or hand dug, clearly explains the depth of the water table in the depression area. The water in the drilled wells may rise to a reasonable depth if the pumps stop for a sufficient length of time, but the effect of pumping is so great that the water drops again after a few minutes. Such an effect was observed in one well of Prince Nayef Bin Abdulaziz at Al-Gurashiyyah, downstream from the Hanifah Dam, where the pump penetrated 64·764 m in the boreholes. When tested by the

Geology Department of the Ministry of Agriculture and Water at the end of a dry season,* it was found that a dishcarge of 4 litres/second continued for seven minutes and then ceased as the water level had dropped from its static level of 40·04 m to the bottom of the bore. The borehole was left for one hour to recover, and then pumping at nearly 2 litres/second started again. It lasted for only one minute and then stopped.

In the areas upstream and downstream from the large depression, the water level also appears to be declining as a result of instant pumping. In the upper reach from Al-Uyaynah village to the confluence of the Wadi Al-Ammariyyah, the general deterioration of the water level between 1948 and 1962 amounted to approximately 25 m. From 1962 to 1972, the record of Hydrology Department of the Ministry of Agriculture and Water shows a drop of more than 7 m in well P606 in the Al-Jubailah area. Unlike the depression area, the upper reach enjoys a more frequent inflow of flood than the lower reach, owing to its nearness to the Wadi water-head. While this advantage dominates here, there is also a possibility of loss of water through sub-flow. The section where the water depth is still unaffected is near Al-Mughaider, possibly because of the inflow from the right bank tributaries, for example, the Wadi Al-Ammariyyah. No recent measurement can be obtained, but according to local inhabitants it falls to about 20 m below the surface. At Al-Ammariyyah village and Abal Kbash in the lower reach of the Wadi Al-Ammariyyah tributary, local farmers claim that it ranges from 9 to 20 m according

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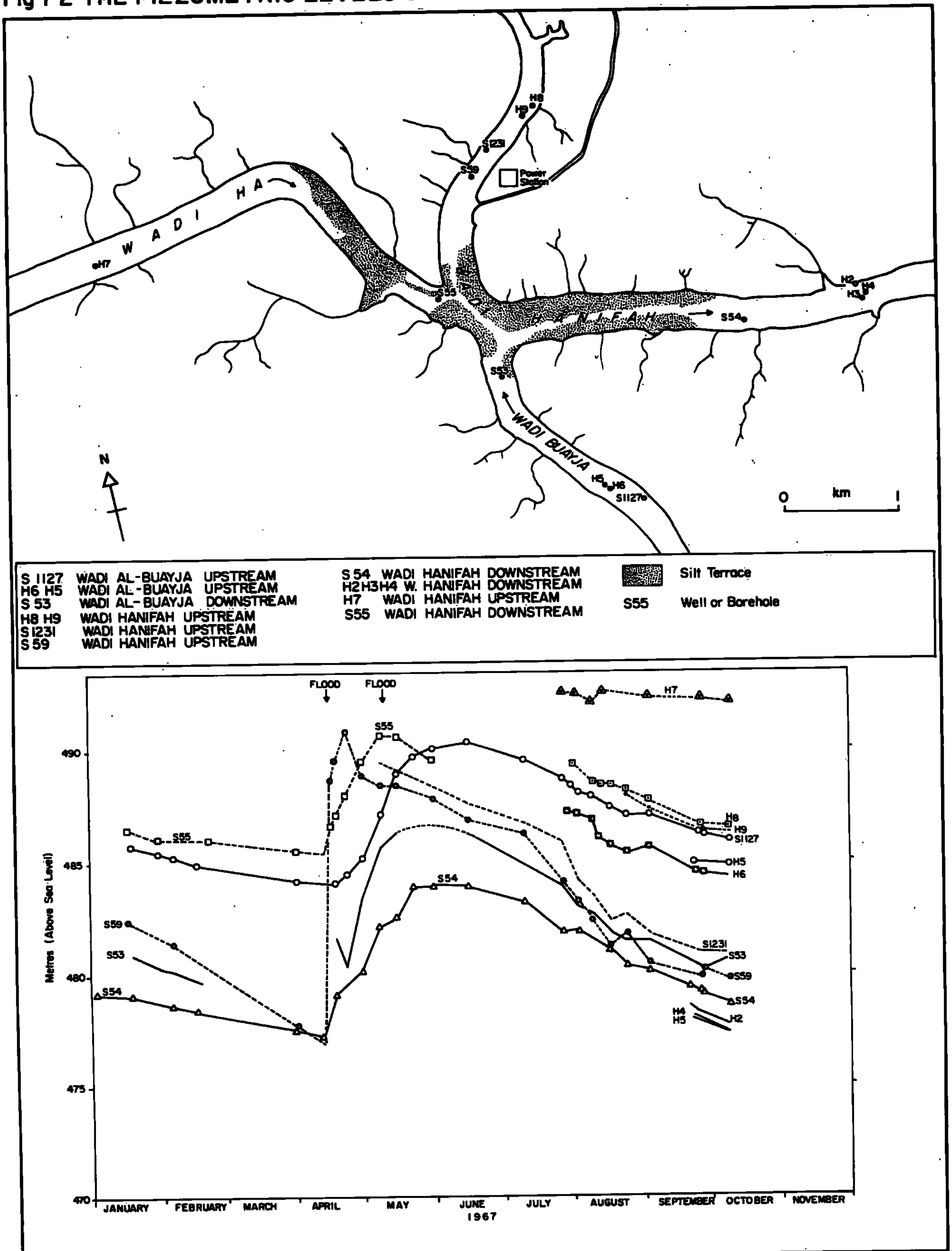
* No date of the record was given in the copy of a report filed in the Geology Department of the Ministry of Agriculture and Water.

to the duration of replenishment.

The water table in the lower reach, particularly in the Al-Ha'ir area (Fig 7.2) used to be near the surface until the drilling of boreholes to supply Riyadh's domestic needs. In spite of an existing cultivated area, irrigated by water from drilled or hand-dug wells prior to the drilling of the Municipal water wells, the water level seemed to decrease almost uniformly and very slightly. Reports following the piping of water to Riyadh in 1956, confirmed a lowering of the water table. Up to 1962, the water table dropped by about 25 m throughout the area (Davis, 1959A). The latest detailed investigation carried out by Sogreah in 1966 and 1967 claimed that the water table depths ranged between 25 and 40 m below ground, depending on the date of measurement (rainy or dry season), and the discharge condition of the tested wells. The variation in water level between dry and rainy seasons changes from one well to another. In the case of unexploited wells - for example S 54 downstream of the confluence of the Wadis Ha and Al-Buayj a - the water level dropped from 21 to 23·5 m below surface during the dry period between March 1966 and April 1967. According to the records of the Hydrology Department of the Ministry of Agriculture and Water, a drop of more than 15 m was also observed between May 1969 and 1970. Although the water level rose 12 m in 1971, it started to deteriorate in the following year. In other wells where pumping is greater, the depth of the water is correspondingly larger. Such a depletion of water cannot be made up completely after the flood, owing to a continuous discharge that is greater than the discharge usual throughout the area. Nevertheless, the rise in the level caused by the flood can be clearly observed, particularly in the exploited wells.

Fig 7·2 THE PIEZOMETRIC LEVELS OF AL HA'IR WELLS IN 1967



Source: Sogreah (1968 A)

In Figure 7.2 the rise of water following flood conditions is obvious. Very often the rise of the water continues after the flood for a period of time before it reaches a maximum. At some wells, for example S59, the recovery caused by the flood in April 1967 continued for only two weeks until it reached its maximum, while at well S54 the water rose for about six weeks before reaching its maximum. Unfortunately, the lack of continuous measurement is a great obstacle when tracing the general decline of the water level in Al-Ha'ir. While the increase takes place in a few weeks, the discharge may continue for a year before the level drops to its minimum, particularly where there is a generous inflow. It is quite clear that the piezometric level in Al-Ha'ir in the previous figure throws light only on the effect of floods upon the recovery of the water table. Determination of the decrease in the water level requires a long period of accurate measurements. Nevertheless, the flood of 1967 in the Al-Ha'ir reach made the water rise in some wells in the Wadi proper by as much as 12 m, for example, S59 well. In other wells downstream from the Wadi Ha and Al-Buayja confluences, the rise did not exceed 7 m, as was the case with well S54. In the lower reach of the Wadi Ha and Al-Buayja, the drop in the water level reached a maximum of 6 m. The variation in the depth of water in the area reflects the heterogeneity of the alluvium, and also the intensity and duration of the flood in each length, which is in turn affected by the width of the channel and the thickness of the alluvium deposit. It can be said with certainty that the main Wadi aquifer at Al-Ha'ir is more affected by infiltration than are the main tributaries, the Wadi Ha and Wadi Al-Buayja, in consequence of its width and the length of the duration of the flood.

However, the water tables in the Wadi Hanifah as a whole vary in depth from one place to another, on the one hand because of extensive pumping, as in the Ergah and Al-Batin area, and on the other because of generous recharge caused by the availability of infiltrated water either through surface inflow, as in the Al-Uyaynah area and Al-Ammariyyah, or through the controlling of the flood by dams for a period of time to permit increased infiltration. Accordingly, the water level is governed by two major factors:-

1) The general decline which has continued since 1948. The gradient of the sub-surface water is more or less horizontal from the upper reach to the area between the confluence of Al-Ammariyyah and Ad-Dir'iyyah, then the hydraulic gradient increases abruptly downstream to Ad-Dir'iyyah, where the water level reaches the channel base. It continues in contact with the base until the area of Manfouhah village, where the water level assumes an almost horizontal surface until the downstream reach of Al-Ha'ir. Throughout the entire length, the hydraulic gradient has been interrupted locally by the impounding dams which have been constructed individually as early as 1959. Thus, for the sake of simplicity, the annual fill in the water level can be defined within four sections of the length of the alluvium channel:-

(a) The section from Al-Uyaynah village to the area immediately under the mouth of the Wadi Al-Ammariyyah (about 25 km in length). The water level here decreases by about one metre every year.

(b) The section from the previous reach to Ad-Dir'iyyah village (about 7 km in length). Annual fall here ranges between 1 m and

3 m.

(c) The Section between Ad-Dir'iyyah village and Manfouhah (a distance of about 30 km). Here the water level had already dropped to the basal alluvium by 1959, particularly at the confluence of the Wadi Nimar, where there is a continuous decline in the water level of about 4 m a year.

(d) The section between Manfouhah and the Al-Ha'ir area (a stretch of about 20 km). Here the fall in the water level is due mainly to the relatively heavy pumping at Al-Ha'ir. The average annual drop is in the region of 0·5 to 0·7 m.

These are approximate estimates, based on the various measurements. However, they do give a broad idea of the constant decline of the alluvium water. Allowing for errors, it can be said with certainty that the minimum fall of the water through the whole length of the exploited aquifer is in the region of 0·4 m per year. Again, the maximum fall of the water table in local areas was 4 m per year.

2) The seasonal fluctuation in the water level which has occurred since the onset of the present climatic regime. When measurement started in 1948, the fluctuation of the water was observed from time to time. Such variation is controlled by infiltration, which is in turn controlled by the heterogeneity of the alluvial deposit, the width of the channel and the density and duration of the inundations. The average variation of the water level was reported by Otkun (1968) to be about 6 m. Such fluctuation starts one or two days after the flood accumulates in the surface channel. The water then rises for either a few days or a few weeks, depending on the recharge and discharge conditions of a particular well.

When the water reaches its maximum, it may stabilise for a week or more, in the case of an unexploited well, or when a succession of floods takes place. The diminishing of the water starts gently during the rainy season, restrained by the relatively low discharge. In the earlier half of autumn, the rate of water extraction appears to be comparatively small, which in turns allows some degree of stabilisation in the water depth. According to the record of Well P606, immediately upstream from Al-Jubailah village, taken by the Hydrology Department of the Ministry of Agriculture and Water between 19.10.70 and 4.6.72, the maximum water level was 28·70 m beneath surface and occurred on 7th May 1971, the minimum level was observed on 4th September 1971, when the water reached a depth of approximately 32·84 m below surface, reflecting heavy extraction in the summer for irrigation. Such variation cannot be applied to each year because of the variations in the times of occurrence, the density and duration of the floods. The most affected area in the whole length is the depression section between Ad-Dir'iyyah and Manfouhah. Here the Dams of Hanifah, Liban and Nimar create the possibility of recovering a great deal of water in a short time. Records show that during the rainy season of 1958-59, despite the impact of the Hanifah Dam, the water level in its vicinity increased by only 5 m and diminished again at the beginning of the following dry season (McCann, 1959). According to new records taken by the Hydrology Department during the hydraulic year 1969/70 at two wells downstream from the Hanifah Dam, the fluctuation ranged between 21·43 and 42·92 m below surface. Such a wide variation between maximum and minimum levels of water in the large depression throws light on the depleted state of the aquifer and the rapid recovery caused by the Hanifah Dam. In the Al-Ha'ir region, the range is between 6 and 12 m.

However, it is quite obvious that the water authorities are aware of the rapid depletion of the alluvial aquifer, not only at the Wadi Hanifah but throughout the whole country, where the traditional balance between man and his environment has been disturbed. Thus, the construction of impound dams in the main channel of the Wadi Hanifah and some of its tributaries creates both an advantage and a disadvantage. The advantage concerning the water level in the wadi is that the ground water may be controlled at some local spots where an intense concentration of drilled wells exists. The disadvantage is that when the flood is small in density and duration, such dams may prevent the flood from flowing to the lower reaches. At the same time, loss by evaporation makes the flood too small to be effective.

It can be assumed that the lowering of the water table in the wadi will continue over coming years. The upper reach beyond Ad-Dir'iyyah is unlikely to drop fast, but it may fall slowly to a point where the discharge will depend totally on seasonal replenishment. Such a level may be expected during the coming two decades. In the case of the large dpression between Ad-Dir'iyyah and Manfouhah, the level of the water has dropped to the fissured limestone, except for the section where the dams exist. The level in Al-Ha'ir area is falling now, but the two tributaries, the Wadi Ha and Al-Buayja, may add a substantial volume of replenishment and allow the aquifer here to last longer than in the upper reach.

7.2.2 Conditions of Recharge

The recharge of the aquifer is controlled by the wadi flow, which is in turn restricted by the shape and size of run-off, and the lateral flow from the adjacent layers. The Wadi Hanifah is unique in its character and orientation compared with the neighbouring wadis, i.e., the Wadi Nisah to the south, and the Wadi Salboukh to the north. The Wadi Hanifah, unlike these wadis, drains its channel in a north-west/ south-east direction, which is favourable in two respects. First, the head of the main Wadi rises, as do other wadis, in the Tuwaig Mountain, with a dense system of feeders joining it at the foot of the mountain, and it flows rather steeply. Because of the geological factors which govern the behaviour of the drainage, the wadi turns to the south, where a large number of tributaries, most of them locally considered wadis (for example, the Wadi Al-Ammariyyah) join the wadi at a more or less steep gradient, which largely avoids evaporation loss. Secondly, as these wadis flow in a similar direction, they flush the flood in a relatively small area, which aids recharging.

The factors restricting recharge are the occurrence of seasonal rainfall, the density and duration of accumulated floods. Before recorded history, the Wadi Hanifah, as well as other Arabian wadis, are believed to have enjoyed a more constant precipitation which sculptured the general relief of the area (Abul-Ela, 1965B). The site and relative length of the Wadi Hanifah indicate that it has had an efficient recharge, even during the past 14 centuries. The wadi has also sometimes suffered from droughts lasting several years.

Investigations carried out in the last three decades have mainly been concerned with the volume of recharge and the factors governing it. Studies have been undertaken by different bodies, primarily by the Ministry of Finance prior to the establishment of the Ministry of Agriculture and Water, and jointly by the Water Resources Development Department and the US Geological Survey. In addition, the master plan for water exploration and development has been undertaken by foreign consultant firms; but all these studies have failed to provide an accurate evaluation of the water recharge in relation to human use and human distribution within the Wadi Hanifah. However, this is the quite understandable consequence of social and economic change within the area. The planning authorities controlling water generally tried to make use of the aquifer for urban supply, and therefore none of the studies has surveyed the entire aquifer; this is especially true of the last investigation, carried out in the late 1960's.

The recharge of the Wadi Hanifah alluvium aquifer is obtained in two ways:-

(1) Direct recharge percolated through the channel surface and retained in the aquifer;

(2) Indirect recharge occurring from the adjacent Jubaila limestone as a lateral flow through the fracture and joints of the unit.

(1) The predominant mode of recharge is by direct infiltration along the wadi course. It is generally true that any volume of run-off (excluding evaporation) entering the wadi channel in the catchment area is likely to percolate downwards and move along the stream. Here, the main difficulty is defining in detail the up-rising and depression within the channel

bottom. Despite attempts to shed light on this subject, a detailed investigation is badly required.

The first attempt to determine the volume was carried out by McCann (1959) during the 1958-59 rainfall season. The investigation relied on determining the volume of water collected in the impound Wadi Hanifah Dam. This was used as a basis for estimating the amount of water that could sink downwards to the aquifer. The volume of water within the impound reservoir was estimated to be in the order of $2{\cdot}5 \times 10^6$ cu m. After deducation of the volume of water evaporated, the remainder must have been added to the aquifer reserve. Another volume of water was measured by Ralf M Parsons Engineering Company in 1959, in the long section between the Wadi Alaisan and Al-Ha'ir village, within four days of the rainy period. An estimated $0{\cdot}672 \times 10^6$ cu m replenished the aquifer (Davis, 1959A).

These records gave a possible volume of water, which, in the case of the Wadi Hanifah, was of value in view of the time when the water could be extracted. Since the places where the records were obtained lie within the cultivated area, the recharge could be extracted immediately, thus preventing the loss of water by underground flow to the lower part of the wadi.

A more accurate investigation was carried out by Sogreah in 1966 and 1967. The volume of the flood passing a section located downstream from the Wadi Ha confluence at Al-Ha'ir, on 13th, 14th and 15th April 1967 was estimated as $4{\cdot}0 \times 10^6$ cu m. Another section, set up at the same time, 40km further downstream, yielded a measurement of $0{\cdot}6 \times 10^6$ cu m. There are no confluents to the wadi between these points of measurement, and the percentage of lateral flow through the banks is very low. The calculation, based on the measurements, assumed that a rate of infiltration is more or less proportional to the surface flow, and it allowed for loss by evaporation between the two points during the three days. It led to the conclusion that the quantity of water infiltrating to the Wadi aquifer was about $3 \cdot 0 \times 10^6$ cu m. The volume which enters the aquifer within this reach has less practical value than that entering the upper reach - between Al-Ha'ir and Al-Uyaynah. Even if the aquifer here is workable and extractable, the channel is comparatively narrow, and this, coupled with the nature of the surface deposit, does not encourage settlement. This area must inevitably be considered in connection with the Wadi As-Sahba system because of the agricultural unity of the region.

The aquifer between Al-Uyaynah and Al-Ha'ir lies in an area where farms and gardens have flourished for a long time; unlike the lower part of the wadi, the alluvium aquifer here lies within the main channel and the lower part of its confluents. The recharge conditions seem favourable, and the volume appeared to be high. According to the measurement of the floods, in 1967-68 (Table 7. 1), the volume of recharge to the alluvium bed in the two specific years was about $57 \cdot 0 \times 10^6$ cu m. The fraction of surface flow infiltrated was approximately 82 % in winter and 67 % in spring. The water infiltrated in the tributary channels is excluded, though this presents a substantial quantity.

Some elderly people, interviewed in Ad-Dir'iyyah and Al-Ammariyyah, reported that two factors influenced the alluvium recharge. Firstly, when the wadi channel was filled with the flood early in the

TABLE 7.1

The Recharge of the Alluvium Aquifer between Al-Jubailah and Al-Ha'ir (1967-68)

(Volumes expressed in 10^6 cu m)

Descriptions	Dates of Measurement			
	April 1967	November 1967	February 1968	April 1968
Volume of flood	11·700	16·700	23·800	24·300
Volume infiltrated	8·100	13·800	19·500	16·000
Average infiltration per kilometre*	0·104	0·177	0·250	0·205

* The total length is 78 km.
After Sogreah (1968A).

rainy season (from November to February), a rise in the water level of the wells was common. This could be explained by the fact that in those months the temperature is relatively low, and therefore evaporation is insignificant. Additionaliy, at this time of year rainfall is of rather lengthy duration (this has been confirmed by the survey undertaken in 1967 by Sogreah). Secondly, one peasant who had observed the effect of inflow on the recharge reported that there was a definite recharge of the aquifer in the area of Al-Jubailah and Al-Uyaynah within the upper reaches when the flood took place in some of the tributaries to the upper reach. Which tributary has the greatest effect on the ground water recharge was not stated.

However, the recharge within the length of the wadi is not necessarily produced by one large flood, as the observations of local inhabitants and the rainstorm system both indicate that the southern part, the 'Al-Ha'ir sub-drainage area', for instance, can be affected by a series of rainstorms outside the area, which in turn produce a substantial inflow, and consequently raise the water level.

During the winter, the surface flow of the wadi proper may take two or three times a year. Sometimes the surface is insignificant in density and duration, and is retained in the main impound dams, i. e., Hanifah Dam, Leban Dam and Nimar Dam. This kind of minor flood has a great effect on the replenishment of the aquifer, but within local sectors.

An attempt was made by Sogreah in 1968 to estimate the floods which are likely to have recharged the alluvium over a period of 20 years. The estimate was based on the rainfall records of Riyadh airport and on direct observations. The results claimed that over 20 years the surface flow in Al-Ha'ir should have been of the following order:-

1 flood equivalent to $8\cdot0 \times 10^6$ cu m	
1 flood equivalent to $7\cdot0 \times 10^6$ cu m	
1 flood equivalent to $6\cdot0 \times 10^6$ cu m	
2 floods equivalent to $5\cdot0 \times 10^6$ cu m	$72\cdot0 \times 10^6$ cu m
2 floods equivalent to $4\cdot0 \times 10^6$ cu m	
4 floods equivalent to $3\cdot0 \times 10^6$ cu m	
6 floods equivalent to $2\cdot0 \times 10^6$ cu m	
9 floods equivalent to $1\cdot0 \times 10^6$ cu m	

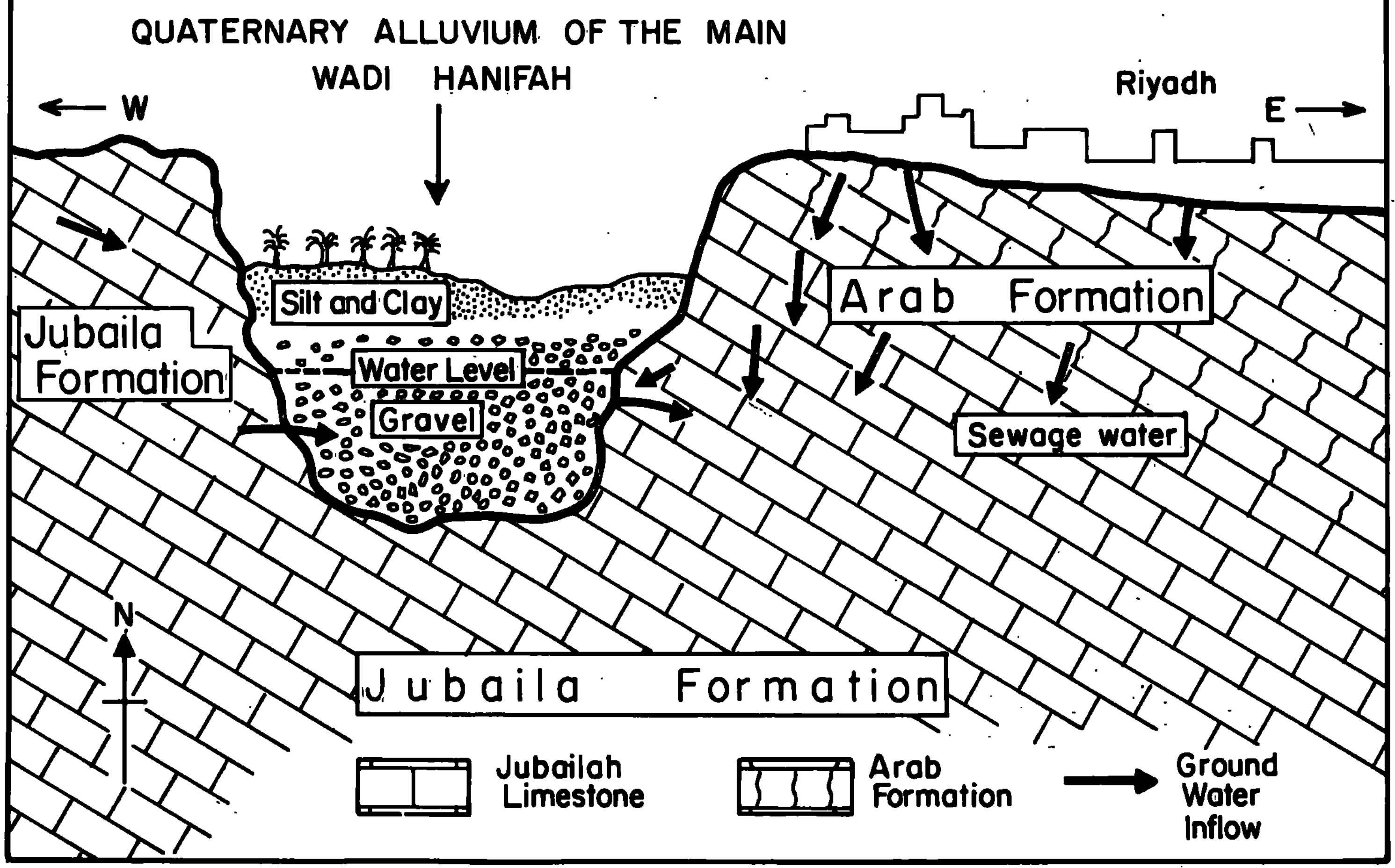
In addition to these results, small floods may also have occurred in the upper reach of the wadi, and been mainly blocked behind the dams. Fourteen floods of this order may have taken place in the twenty-year period, and they would have had a significant effect on the aquifer recharge.

To determine the average annual replenishment of the entire aquifer according to the preceding remarks, one must have the annual average of surface flow, which occurs throughout the whole length of the main Wadi Hanifah. According to the frequency and quantity of surface flow, the average amount of the overall surface flow is $18\cdot4 \times 10^6$ cu m or more per annum (Sogreah, 1968A). To estimate the quantity of water recharging the aquifer, the average annual amount of surface flow passing Al-Ha'ir (i.e., $3\cdot6 \times 10^6$ cu m) must be deducted from the average overall annual surface flow of $18\cdot4 \times 10^6$ cu m. Thus, the average annual replenishment to the alluvium aquifer is about $14\cdot8 \times 10^6$ cu m. A relevant factor here is the distribution of the discharge area, which is scattered in the main confluents and the places where the silt terrace is suitable for cultivation.

(2) The other indirect mode of recharge supplies the alluvium aquifer

via the Jubaila limestone. The latter unit is fissured and fractured, so that a quantity of water is held within the fissured limestone. It is also obvious that the alluvium deposit in the exploitable section between Al-Uyaynah village and Al-Ha'ir area lies in the channel cut by the main wadi between the limestone strata. In other words, the limestone underlies and embraces the alluvium deposit. Consequently, the bed of the wadi channel is, in fact, based on permeable layers of the limestone. It is possible that the banks of the channel may receive a portion of the water stored in the fractures, particularly when the water table of the alluvium drops as a result of discharge. Before the introduction of mechanical pumps, when the balance of water favoured storage, the water in the fractures of the limestone might have had the same level as the alluvium, and a connection between the two units may thus have been formed. Thus, the water of the limestone joined the water in the alluvium in the direction of the water flow, which would have had to follow the dipping of the strata from west to east. If this assumption is correct, the direction of flow must be the same now. In addition, the abundant water recharging the limestone in the urban sector, Riyadh City, may replenish the alluvium aquifer in the opposite direction to the slope of the strata (Fig 7.3). One piece of evidence supporting this theory is that the sewage water of Riyadh City has made ground water in the limestone rise up near the surface of the ground in some parts of the city. Thus, the alluvium aquifer in the western part of the city may receive some replenishment, particularly when the level of the aquifer decreases in the heavily pumped areas, for example Al-Batin, Ergah and Ad-Diriyyah. The existence of underground water in the fissured

Fig 7·3 Sketch Showing Underground Water Transfer Between The Alluvium Aquifer and the Adjacent Jubaila Limestone



limestone beneath the bed of the Wadi Hanifah was confirmed by drilling two boreholes in the vicinity of Hanifah Dam (HD 10 and HD 11), as well as one borehole (in 1967) in the area downstream of Al-Ha'ir (H2). When the latter borehole was drilled, the water table reached a depth of 50 m below the surface. Because the unit was highly fissured and the water was under pressure, it rose by about 22 m, slightly above the water table of the alluvium water. If the two units - the alluvium and the fissured limestone - are connected hydraulically, then alluvium water might seep through to the limestone. This is, however, unlikely, since the high level period in the alluvium aquifer is too short to allow water to escape. It is more probable that the water in the limestone, being under relatively high pressure, should flow to the alluvium. The lateral movement from the limestone was noticed in the late 1950's, when similar samples were taken from different wells at Al-Uyaynah in the upper reach as well as the section between Ad-Dir'iyyah and Ergah in the middle reach (McCann, 1959).

A considerable increase in the mineral content of the alluvium water in these samples gives some evidence that the limestone water must have invaded the alluvium aquifer in the rural sectors, since the installation of motor-driven pumps. There is no possible record determining the quantity of water recharging the alluvium water in the rural sectors.

In the metropolitan area of Riyadh City, the limestone aquifer is heavily charged by the sewage water of the city. Here, the water is drawn from different sources, for example Minjur aquifer, Wadi Alluvium, and the Jubaila aquifer itself. The amount of recharge to the limestone is found to be 40% of the consumption of the urban area (Sogreah, 1967), including the city water supply, the private well penetrating the Jubailah, and other boreholes extracting water from the Minjur aquifer. $1{\cdot}7 \times 10^6$ cu m are estimated to recharge the Wadi Hanifah water table in the area flanking Riyadh city.

Until further investigation determines the amount by which the limestone in the upper reach recharges the alluvium water table, greater accuracy is impossible. It is, however, at least clear that this factor must affect the local water table, replenishing the aquifer when the water there is at a lower level.

7.2.3 Conditions of Discharge

The alluvium has gradually been losing its store of water over the past three decades. Looking at storage before that date, it is possible to deduce the recharge and discharge conditions which maintained the Wadi Hanifah settlements for so long. To this end, it is first necessary to establish the factors that have accelerated discharge and disturbed the historical water balance in the Wadi Hanifah proper, chief of which has been the changing pattern of water extraction and use since 1948.

A field trip by the author in February 1974 on an eighty-kilometre stretch of the Wadi Hanifah, from near the area upstream of Al-Uyaynah to a point south of Al-Ha'ir, revealed that the alluvium aquifer was penetrated by hand-dug wells of different sizes, located mainly in the silt terraces within the banks of the main wadi and the major tributaries, The maximum depth of the wells was 30 m, from which depth the animals can lift the water by skin-pocket (Gharb). Wells used for cultivation must have an oblong shape, as the wooden wheels need to be arranged parallel to one of the sides. Water-raising by animals is called Sanyah (pl Sawani). The number of animals operating one well depends on the size of the well; usually about four animals work on one side of the well. A few large wells can be operated from two opposite sides by eight animals. The volume of water extracted from the well depends on the level of the water, since this governs the distance the animal goes and returns. In other words, if the level of the water is 5 m from the surface, the time interval between raising and re-raising the filled container will be the time taken by the animal in going 5 m away and returning. The quantity of water that can be collected in a gharb varies; generally the camel's gharb is slightly larger than that of a cow or donkey. An earlier attempt to estimate the water extracted per animal per minute was made by the American Mission to Saudi Arabia (1943), and the results are given in Table 7.2. If we assume that the wells in the middle reach of the Wadi Hanifah have a depth of 13 m, a water level 9 m beneath ground level, and four animals raising the water, then the average yield will be approximately 2·48 litres/second (l/s). The quantity of water extracted will decrease as the water level declines (see Table 7.2). The volume of water raised by the animals in one unit of time represents more or less the maximum yield capacity.

With the introduction of mechanised pumps, the amount of water extracted was far greater than the storage capacity of the well. Centrifugal pumps, the type first introduced after 1943 (Nouri, 1974) are

TABLE 7.2

Average Amount of Water that can be Drawn from a Hand-Dug Weil by One Animal

Depth of Water Level Below Surface (Metres)	Volume of Water Extracted (Litres/Second)
1·5	1.86
3·0	1·55
4·5	1·24
6·0	0·93
9·0	0·62
15·0	0·47
24·0	0·33

Source : The American Mission to Saudl Arabia (1943) believed to have increased the water discharge sharply. According to villagers in Al-Uyaynah and Ad-Dir'iyyah, this type of pump became more common in the 1940's and 1950's. Its ease of operation and reasonable price, coupled with the carelessness of farmers and peasants, caused a sharp decline in the quantity of water stored. The same is true of the turbine-driven pump, introduced after the acceleration of discharge had made it impossible to conserve ground water between rainy seasons. Thus, the change from the traditional sanyah to mechanical pumps for raising water was, in fact, responsible for heavy discharge.

Moreover, when the sanyah was in operation, the well itself used to be a reservoir collecting water. Between two intervals of go and return by animals, the water in the well increased. In contrast, the mechanical pumps do not permit water to flow in again at the rate of discharge. In spite of new drilling and deepening to the alluvium basal layer, discharge remains faster than replenishment. As has been observed, this is not the effect of urban invasion only, but also of modern equipment and a lack of wise supervision. According to the geologists and hydrologists of the Ministry of Agriculture and Water, who have observed this phenomenon over the last 15 years, most peasants who contacted the Ministry were concerned with the depletion of the water in their wells. Very often they asked the Geology Department to investigate the possibility of deepening the existing wells in the hope of striking a supplementary water supply.

The wells in the Wadi Hanifah proper can be divided into two categories according to their management (Table 7.3). On one side, we have the wells supplying Riyadh City, and, on the other, those used by

TABLE 7.3

The Annual Volume of Water Exploited from the Alluvium Aquifer of Wadi Hanifah and its Tributaries (10^6 cu m)

Area	Agricultural Use	Riyadh Water Supply
Al-Uyaynah) Al-Jubailah)	5·00*	
Al-Mughaider	1·85	
Al-Amariyyah	3·00*	
Ad-Dir'iyyah	17·30	
Ergah	2·60	
Al-Gurashiyyah	3·05	
Al-Batin (including Wadi Nimar)	13·50	1·20
Manfouhah and downstream	13·40	
Al Ha'ir	0·97	2·20
Total	60·67	3·40

* This volume of water is estimated according to the area of cultivated land.

Sources : Davis, (1959); Sogreah (1968A); Statistics of the Ministry of Agriculture and Water (1964).

private owners.

The wells used for the requirements of the city are mainly found in the Al-Ha'ir area and near the mouth of the Wadi Nimar, to the west of the city. In the Wadi Nimar, downstream of the impounding Nimar Dam, six wells are used for the city's water supply. The water is taken to the houses either by tanker lorry, or by a small pipeline connected to the Manfouhah water tank. All these wells supply a maximum average yield of 50 l/s, and a minimum average yield of less than 30 l/s. The peak value attained when the dam is filled with flood water rises to about 100 l/s. However, though the Nimar wells contain good quality water, their average yield during the whole year probably does not esceed 20 l/s. In the Al-Ha'ir area, 13 wells with a depth of about 50 m exploit the water-bearing alluvium of the Wadi Hanifah and its feeders, the Wadi Ha and Wadi Al-Buayja. The confluence of the Wadi Ha and the Wadi Al-Buayja with the main wadi encouraged the water authorities to drill these wells, since the relatively small size of the confluence zone facilitated the installation of a large complex of extraction works made up of private and municipal wells. Eight out of the 13 wells send the water by pipeline to the city. The area in which these wells were drilled is unique, due to the fact that the junction of the two tributaries with the main Wadi has an alluvial infilling deeper than the adjacent area. The wells in operation, according to the Ministry of Agriculture and Water officials, have a yield of a slightly variable nature, ranging between 120 and 130 l/s.

Privately operated wells are scattered all over the exploited section of the aquifer, between Al-Uyaynah village in the upper reach to Al-Ha'ir in the lower reach. Though the alluvium aquifer has been exploited, in the area of Al-Uyaynah, downstream on a stretch of approximately 61km of the main wadi, is the spot where discharge is heaviest. Here, the wadi silt terraces are highly cultivated. More than 114 hand-dug wells still exist at Ad-Dir'iyyah area, in addition to some 30 or 40 drilled wells of the same dimensions. The Ergah area seems to have been exploited particularly by drilled wells. In addition to this, wells have been dug or drilled in the wadi wherever the terrace is found. In Al-Mughaider, for instance, and immediately upstream of the confluence of the Wadi Al-Ammariyyah and the Wadi Hanifah proper, the silt terrace covers more than half the width of the wadi channel. Here about eight hand-dug wells occur in a small area. After Ad-Dir'iyyah, the most heavily pumped area lies between Al-Batin and Manfouhah downstream. Here also, the wadi has been heavily pumped due to the existence of a widely cultivated area within the silt terraces. Some small villages lie in this section, for example Al-Uraija, Al-Badi'ah, Utay'gah, Manfouhah and Al-Masan'i.

As a result of the lack of water control, the aquifer has been depleted badly. In a comparison between the approximate annual volumes of recharge ($15{\cdot}0 \times 10^6$ cu m) and discharge ($64{\cdot}7 \times 10^6$ cu m), the latter figure is far greater than the former. Accordingly, the aquifer proved to be incapable of satisfying the agricultural need.

In an attempt to save palm gardens in the most depleted areas, such as Ad-Dir'iyyah and Ergah, the Ministry of Agriculture and Water piped water to the area from the Minjur Salboukh boreholes.

7.3 Water Quality

The existence of settlements and cultivation along the Wadi Hanifah is controlled partly by the quality, as well as the availability, of water. The names Al-Ha'ir, Al-Uyaynah, Al-Mughaider, Liban, and Nimar, all originate either from the excellent quality of the water or its plentiful availability, at the beginning, or during the course of human settlement. "Sweet", "bitter" and "salt" are the descriptive categories applied to the water by farmers and villagers. When the inhabitants are questioned about the quality of the alluvial water, their reply is that the general quality is good. When they are questioned about specific wells, in a particular village, they distinguish between different qualities of water. Such distinctions lead to observations that particular qualities of water are suitable for men, plants, or livestock. However, before pursuing the definition of the different qualities, it will be useful to ascertain what kind of water has traditionally been considered acceptable for human use in the area under study.

People living in the Wadi Hanifah have passed through three social stages in the historical epoch; their way of life has been controlled by the quality of water available in their environment. Before the encouragement of the village community by King Abdul-Aziz and also before the growth and expansion of Riyadh City, the Wadi Hanifah , like the rest of the Arabian Peninsula, was occupied by tribal communities, dependent largely on grazing. Such communities were, through the hardness of the desert, inured to variations in the quality of their water. Luckily, the quality of the water of the wadi alluvium aquifer is generally good, and the water is thus suitable for Bedouin use. Polluted water used to be considered drinkable, as long as it was religiously acceptable. So, Bedouin society is fairly tolerant when it comes to the quality of its water. The inhabitants of the villages are more concerned to find water with a low rate of dissolved materials. In other words, people in the villages have the chance to look for water of good quality, but they seem to be quite unaware of the quality of the water in terms of its effect on physical health, caring only for its palatability. The modern society of the city, as well as the surrounding villages, has benefited from the purification treatment of water and from the supervision of the health authorities, who determine the quality of water that people can use.

The quality of the water in the entire wadi alluvium aquifer is considered to be good, although variations in the water can be found in both vertical and horizontal directions. The quality varies according to the age and origin of the water; thus, the recently infiltrated water is found to be of good quality. This water derives from the run-off which drains the catchment, and it accumulates in the wadi channel. It would not be a fair judgement to say that when the water table rises to a maximum level, water quality becomes good. The quality may on the contrary be due to the type of deposit through which the water percolates. But the investigations by different consultant firms led to the conclusion that the recent water is relatively little mineralised. Such water can be found in some main tributaries, like the Wadi Nimar and the Wadi Liban to the west of Riyadh City. The water extracted from another adjacent aquifer and returned to the aquifer itself, as a result of surplus irrigation, seems to be more mineralised than the recently infiltrated water. Such water is common in and near to the cultivated area. Another kind of water with relatively high mineralisation seems to be found when the water table in the alluvial aquifer is very low. Such water moves to the aquifer from the surrounding limestone formations (Tuwaig, Hanifah, Jubaila and Arab) according to their dip slope, or through a lateral sub-surface inflow. Though such movement is very slow, it has affected the aquifer, particularly in recent years. Finally, the recharge in the part of the aquifer to the west of Riyadh City originates from the sewage water of the city, and appears to be highly mineralised and contaminated. This water is probably seeping into the aquifer between the confluences of the Wadis Alaisan and Al-Bat'ha, with the main wadi.

The earliest investigation of the aquifer claimed that, though the water showed an appreciable variation in mineral content, it was generally suitable for domestic use without any treatment (McCann, 1959). It is equally true that, despite a general range of 500 to 900 parts per million (ppm) total dissolved solids (TDS), it is also possible to find local variations of between 1,000 and 2,000 ppm .

The water between Al-Uyaynah and Al-Mughaider appears to have a consistent content of approximately 800 ppm of total dissolved solids. According to McCann (1959), the area downstream from Al-Mughaider to Ad-Dir'iyyah yields a smaller amount of TDS as the subsurface inflow comes from the Wadi Al-Ammariyyah. The water here contains about 500 to 800 ppm. Between Ad-Dir'iyyah and Ergah village, the mineralisation content increases to between 1,200 and 1,500 ppm. Downstream from Ergah village to the Hanifah Dam, a combination of the lateral inflow from the Wadis Wubair and Al-Mahdiyyah, and from the Hanifah Dam, appears to produce a mixture of ground water containing about 650 ppm.

Again, at the confluence of the Wadi Nimar with the main wadi, the water seems to have a low mineralisation content, and the same is true of the Wadi Al-Ammariyyah confluence. The area between the Wadi Nimar and Al-Ha'ir appears to have a comparatively low mineralisation content; while at Al-Ha'ir, the water of the Wadi Ha drains off the Dhruma Plain and contains large amounts of solid, it is ultimately diluted so as to give a relatively low TDS value.

The effect of the subsurface inflow from the large tributaries is combined with the effect of water from irrigation. The percolation of excess irrigation water may contribute substantial quantities of salt. The evaporation process tends to increase the total dissolved salt in the ground water. Such an effect occurs in the Ad-Dir'iyyah area, where there is variation in the mineral content of the water. An example of the combination of these factors is provided by the area between the confluences of the Wadis Liban and Nimar with the wadi proper. Upstream of the Wadi Liban, where irrigation used to take place, the water in February 1958 contained 2,000 ppm of TDS, while further upstream still it contained only about 1,000 ppm. Downstream, a decrease of 400 ppm confirmed the effects of the water from the Wadi Liban, which has a salinity of about 350 ppm (Davis, 1959B). In the case of the section near the confluence of the Wadi Nimar, the area upstream appears to have a constant salinity of about 950 ppm, while at the mount of the Wadi Nimar the ground water contains only 500 ppm. From the Wadi Nimar downstream to the confluence of the Wadi Al-Bat'ha, near Manfouhah village, there is a cultivated area where the salinity of the water tends to increase to 1,200 pp. Downstream to Al-Ha'ir, the salinity again decreases to

800 ppm in consequence of the relatively low and scattered agricultural activity, coupled with the contribution of the surface inflow from the small tributaries in both banks of the wadi (Davis, 1959B). It is quite certain that when the water table falls to a considerable depth, there is likely to be an invasion of water from the fractured limestone. In the areas which were the first to be affected by drilling, particularly near Ergah village, the total dissolved solid ranged between 1,200 and 2,000 ppm in 1959. Here the water level has varied considerably, and this has permitted lateral replenishment from the adjacent limestone. The recent investigation by Sogreah (1968A), confirmed an increase in mineralisation in the Ergah section and the area upstream. Irrigation water must also have produced some effect, for the Ad-Dir'iyyah area is intensely cultivated. The cause of the accumulation of solids has long been a subject of uncertainty. Salt may have accumulated because the percolation of water through the silt terrace is very small, and the evaporation rate is relatively high. Nevertheless, a comparison of two samples taken in 1948 and 1958 shows that the dominant factor is replenishment from the Jubaila limestone. The samples reveal that an increase of about 300 ppm was detected in the Ad-Dir'iyyah area, while at Ergah village the water had, in 1958, declined 25 m, and the total dissolved solids ranged between 1,200 and 2,000 ppm. These results indicate that despite the large cultivated area around Ad-Dir'iyyah, it is the drilling at Ergah and the lowering of the water level which has brought about the increase by occasioning interference from the ground water in the adjacent fissured limestone.

Recently, the Riyadh water supply has affected the quality of the water between Al-Ma'ther - north of Riyadh City - and the area downstream from Manfouhah village. It is too early to determine the exact rate of effect, owing to insufficient investigation coupled with the complicating factor of the sub-flow from the limestone. The sub-flow to the alluvium aquifer comes originally from the Minjur water and from the Jubaila limestone water, and this water eventually recharges and affects the alluvial aquifer water. The sewage of Riyadh City, which replenishes the limestone, contributes some sub-surface water to the alluvium. In addition, Minjur water from Salboukh deep wells has been recently supplied in the dry season to the cultivated areas at Ad-Dir'iyyah and Ergah, and this may also have affected the quality of the ground water.

The latest samples taken by Sogreah in 1967 and 1968 can be classified as follows:-

(1) The Wadi proper. Samples taken from upstream, between Al-Uyaynah and Al-Mughaider have a relatively uniform chmeical content. Average values of 1,540, 1,760 and 1,300 micromhos/cm at 25°C (1,080, 1,230 and 910ppm of TDS) are recorded from Al-Uyaynah, al-Jubailah and Al-Mughaider respectively. In the section of the wadi channel between Ad-Dir'iyyah and Ergah the salinity increases in a downstream direction. The increase rate ranges from 1,500 to 4,000 micromhos/cm (1,050 to 2,800ppm of TDS). Downstream from Ergah village, the samples reveal less salinity; 1,500 micromhos/cm (1,050ppm of TDS) is detected in the small farmed area near the Hanifah Dam. At Al-Gurashiyyah, a large variation in salinity is present, ranging between approximately 600 and 3,000 micromhos/cm (420 and 2,100 ppm of

TDS). From Riyadh downstream to the Al-Ha'ir area, the salinity varies from place to place. For instance, near Riyadh changes in chemical composition have been traced. There is as much sulphate as chloride and the magnesium content almost equals the sodium content. Thus, salinity increases in some localities. At Manfouhah village, a range from 6,000 to 7,000 micromhos/cm (4,200 to 4,900 ppm of TDS) is noted by Sogreah. Another report from this section was made by Davis (1959B) who found that the water in a well 4km downstream from the Wadi Al-Bat'ha confluence contained 2,750 ppm of TDS. Thus, the quality of the water in the main channel of the Wadi Hanifah varies from one spot to another as a result of the mixture of water from different sources.

(2) The quality of the water in the main tributaries seems comparatively good. The Wadi Al-Ammariyyah water had a value of 900 micromhos/cm (630 ppm of TDS) in 1967. The Wadi Nimar had a similarly low value. This wadi is known among the inhabitants of Riyadh for its good quality water; it is quite common for travellers on the Riyadh-Taif highway to see a long line of cars and an equally lengthy queue of people filling water containers from a tap situated a few hundred yeards from the right bank of the Wadi Nimar. As the water is of good quality, this tap has been provided for tanker lorries and car drivers. Thus the water of the Wadi Nimar is of good quality, but its volume is small.

The mineralisation of the ground water in the Al-Ha'ir area varies from one well to another, depending on the spot where the wells are located. This fact was first established by Meyerhofer (1958) when he gave an estimate of the chemical deposit detected from conductivity in the Al-Ha'ir wells. Though he failed to correlate variation with well location, an average of 844 ppm of total dissolved salts was given for Al-Ha'ir water. The survey by Sogreah which involved the sampling of water in the Wadi Hanifah proper and in the Wadi Ha, revealed the local variations. Though ground water at the Wadi Al-Bdayja has not been sampled, the Wadi Ha ground water shows a lot of the variation. According to some of these samples taken from the Dirab area, 25 km west of Al-Ha'ir, a range of 3,200 ppm to 5,619 ppm is found, while at well S 615 in the lower reach the analysis gives 1,980 ppm. This high rate of mineralisation in the Wadi Ha in general results from the high salinity of the Dhruma plain, which is the drainage area of the Wadi in its water-head and upper stream. The low rate of mineralisation in the lower stream is probably a consequence of the infiltration process in the Tuwaig mountain and adjacent formations. In the Al-Ha'ir area of the Wadi Hanifah proper, the very low rate of mineralisation upstream of the Wadi Ha confluence increases gradually in the downstream section. Samples taken from boreholds S 621 anc S 216 in the upstream area give rates of 435 and 565 ppm respectively. Analysis of other samples from the downstream area revealed that the mineralisation rate is 1,620 ppm for well S 603 and 2,000 ppm for well S 604. The low rate for the ground water upstream from the main wadi is due to the short period it has spent underground in the alluvium. The comparatively high rate in downstream wells is caused by the inflow of the Wadi Ha, which is more mineralised, and also by the percolation of irrigation water applied to the farms of the Al-Ha'ir area.

Finally, it is quite safe to say that the great bulk of the alluvial aquifer contains water of good quality. The increase of mineralisation is connected with recent development, which has caused a lowering of the water level, and consequently more invasion by water from adjacent fissured limestone, and by surplus sewage water from the urban area.

CHAPTER EIGHT

THE JUBAILA LIMESTONE AQUIFER

Historically, the Jubalia limestone along with the Alluvium Aquifer used to be the backbone of the water supply of the region of Wadi Hanifah. While the Alluvium Aquifer supplied water to the rural area of the wadi, the Jubaila Aquifer was used mainly within the old city of Riyadh and its surroundings.

Owing to the latest development of water and the expansion of the city, the Aquifer is left nowadays without any significant use.

The outcrop of the Jubaila limestone extends along a comparatively wide belt on the foot of the Tuwaig Mountain, (see Figure 3.1).

Although its thickness reaches about 130 m, the Aquifer is traced only within a vertical section of approximately 30 m from the top of the formation. Here the limestone is mainly karst, with open cracks and fractures, the effect of strong solution. The fractures have developed, in some places, to large cavities and connected channels. Water, as a result, is restricted to the fractures and cavities. In other words, it is mainly derived from inflow through the fractures rather than from the porosity of the rocks themselves.

Such a phenomenon is seen clearly in trenches dug for water mains, telephone cables and electricity in the city of Riyadh, and particularly in the central and western parts. In some places, these trenches may reach the water table, which is rising as a result of sewage disposal. The cracked condition was also observed by Sogreah (1967) in Well P632, at Um Al-Hamam in the middle reach of the Wadi Alaisan, and at Well P629 at Al-Ma'ther, in the lower reach of the same wadi (Fig 8.1). The cracked limestone in these wells appeared to be within the uppermost portion of the formation. The jointing and fractures are copious underneath the alluvium deposit rather than where its outcrop exposes on the surface. In some places the fissuring is shallow, while in other areas it may continue to a considerable depth. It seems obvious that the fissuring of the limestone is more deeply weathered and dissolved by water beneath the alluvium deposits than outside them. Outside the small valleys, the depth of the cracked or fractured limestone is shallower and more irregular; one example of this is the area between Riyadh City and Al-Ha'ir village, where a drilling of three boreholes took place near Well P 106. One of the boreholes struck water, whilst the remaining two were completely unproductive. Similar phenomena can be seen in the city of Riyadh and its surrounding area. Drilling carried out between 1950 and 1953 showed that 20 out of 70 boreholes had been abandoned due to missing any large cracks in the area.

The water of the Aquifer has kept the old city of Riyadh supplied for many years, mainly for domestic use and irrigation purposes, particularly in the area near the wadi channels. It is rather difficult to obtain a record of the number of wells which penetrated the Aquifer in the city, due to the absence of data giving details of the number of water points and the number of houses in the city at that time. The manner in which the site of digging a well was decided was related to the size of the city, its location in relation to the Wadi Hanifah basin, and above all the pattern of social and religious structures, where the

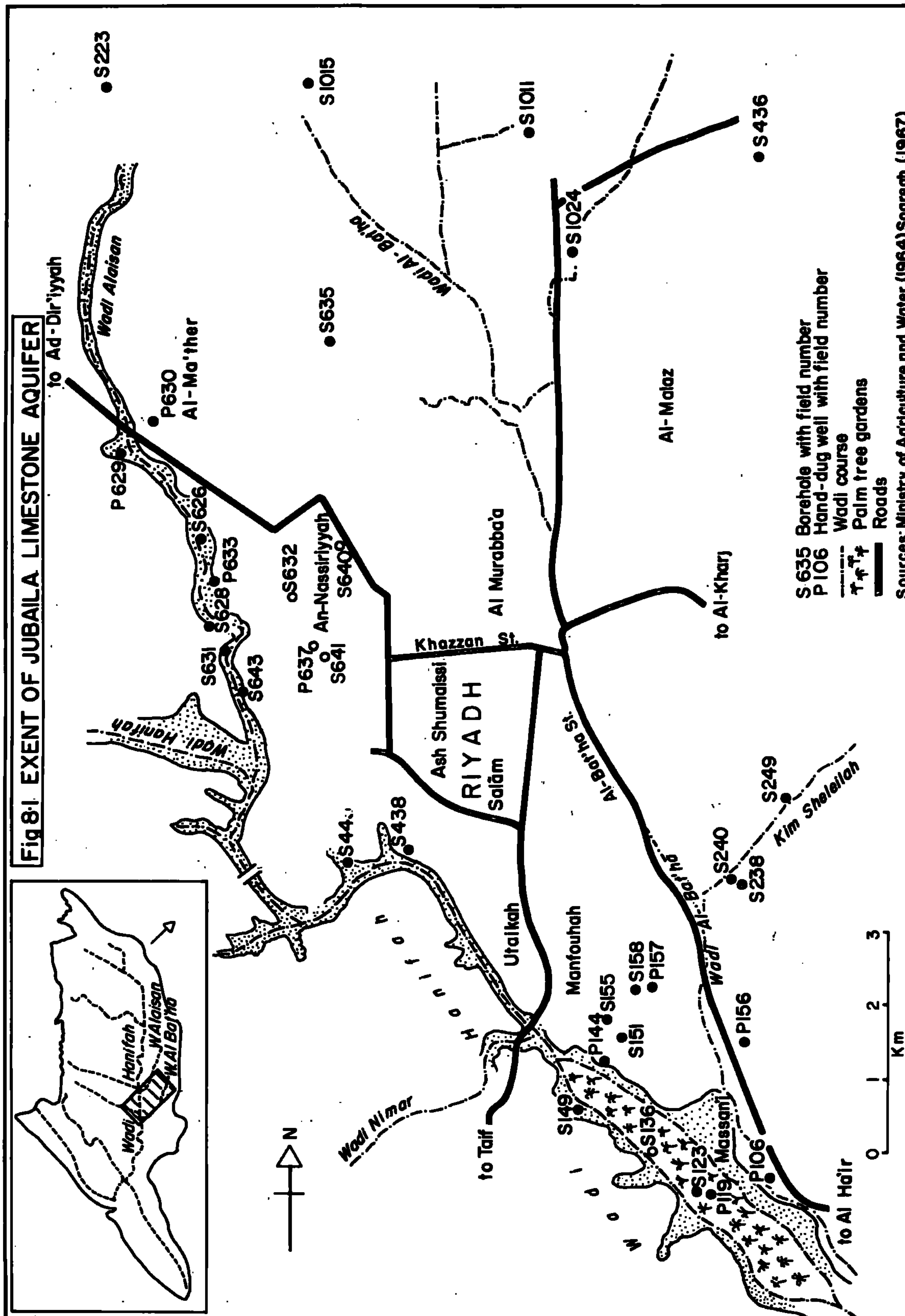


Fig 8·1 EXENT OF JUBAILA LIMESTONE AQUIFER man was the financial provider and the woman took care of the domestic and housing problems. Water was extracted from wells in and near the cultivated areas, which are distributed either in the silt terrace of the wadi proper in the northern part of the city, or at the outwash fans of small wadis which have been diverted to flat plains or slumped areas around the city. Thus, the maximum potential of the Jubaila Aquifer is relaised in the area of Riyadh City, as well as in Um Al-Hamam on the Wadi Alaisan, in the Wadi Al-Bat'ha basin to the north, and in the Manfouhah and Al-Masan'i area to the south (see Figure 8.1).

8.1 Conditions of Recharge

The recharge of the Aquifer comes primarily from the wadi channels which cross the outcrop. The middle course of the Wadi Hanifah proper recharges the Aquifer through the saturated alluvium deposits. However, although the main wadi has the major surface inflow within the region, the recharge of the limestone appeared to be from the left bank tributaries, for example the Wadi Alaisan and the Wadi Al-Bat'ha. Here the alluvium obscuring the limestone within the channels is rather thin when compared with the one of the Wadi Hanifah proper; also, while the Wadi Alaisan rises from the Arab formation outcrop, the bulk of the flood flows smoothly along the 10km length of the wadi. The fracturing phenomena in many places along the course of the Wadi Alaisan, especially at Um-Al-Hamam in the upper reach and Al-Ma'ther in the lower reach, support this idea. In addition, observations and investigations carried out by Sogreah in 1967 confirmed that the Wadi Alaisan still adds its own recharge to the Aquifer when seen from the piezometric gradient upstream from the Al-Ma'ther area in the vicinity of the northern part of the city.

Sewage water from the old city also contributes to the constant recharge; thus, water consumed in the city finds its way to the upper portion of the limestone. Prior to 1948, when Riyadh City was in its earlier stages of development, water consumption was rather small, but since then the expansion of the city in all directions has meant that the Aquifer is being replenished with large quantities of waste water. This replenishment occurs all over the city area because of the technique by which the sewage system is operated. Thus the sewage water does not flow in a sewage pipe network; instead, every house has a hand-dug pit penetrating from two to four metres downwards through the limestone. The digging usually takes place on the adjacent road and the pit is connected to the house by a pipe, and although there are no records, it is quite certain that each house has a sewage pit outside.

Also, run-off occurs after a rainstorm in the city, supplying a substantial amount of water. This storm-sewage is diverted to the old hand-dug wells, scattered about the city, which formerly supplied water to the cultivated areas around the city. The expansion of the city over-ran the farms and gardens, and their wells were covered and eventually used for rainfall sewage.

Thus the water percolating to the Jubaila Aquifer at the present time comes mainly from the Riyadh water supply, which is in turn derived mainly from the Minjur sandstone. The recharge of the Aquifer both from sewage pits and irrigation water depends basically on the cracked condition of the limestone. The potential amount of water used in the city has increased, and is still increasing, due to rises in both population and the number of houses. The water consumption of the city in 1959 was in the order of $9 \cdot 0 \times 10^6$ cu m. Of this, $4 \cdot 0 \times 10^6$ cu m were consumed in An-Nasiriyyah area in the west of the city (Davis, 1959B). This water distribution has left its mark on the piezometric water table around the city down to the end of the recent survey. From 1960 to 1967, the areas providing the bulk of used water were mainly An-Nasiriyyah, Al-Ma'ther (north) and Al-Malaz area (north-east), as in these areas the modern buildings have the advantage of piped water. Though the remainder of the city has the same facilities, the sewage discharge is comparatively larger in the western and northern parts.

However, in the northern part (An-Nasiriyyah and Al-Ma'ther), the irrigation flow of the gardens appeared to comprise 200 l/s, three-quarters of it extracted from the Minjur water beneath the region. Twelve to 15 % of this water percolates down to the water table, which means that the recharging flow to the Jubaila limestone must be about 20 l/s. In the autumn of 1967, Riyadh consumption was recorded as $0 \cdot 075 \times 10^6$ cu m per day, and in the autumn of 1973, it rose to $0 \cdot 08484 \times 10^6$ cu m per day, and is expected to be $0 \cdot 118 \times 10^6$ cu m at the end of 1975 (Agric Guidance Bull No 3, 1973). According to Sogreah's survey, 40 % of the water used in the capital city sinks down to the water table of the Jubaila limestone, the inference from this being that $0 \cdot 0472 \times 10^6$ cu m per day are recharding the Aquifer. Additionally, the flood accumulates and flows along the Wadi

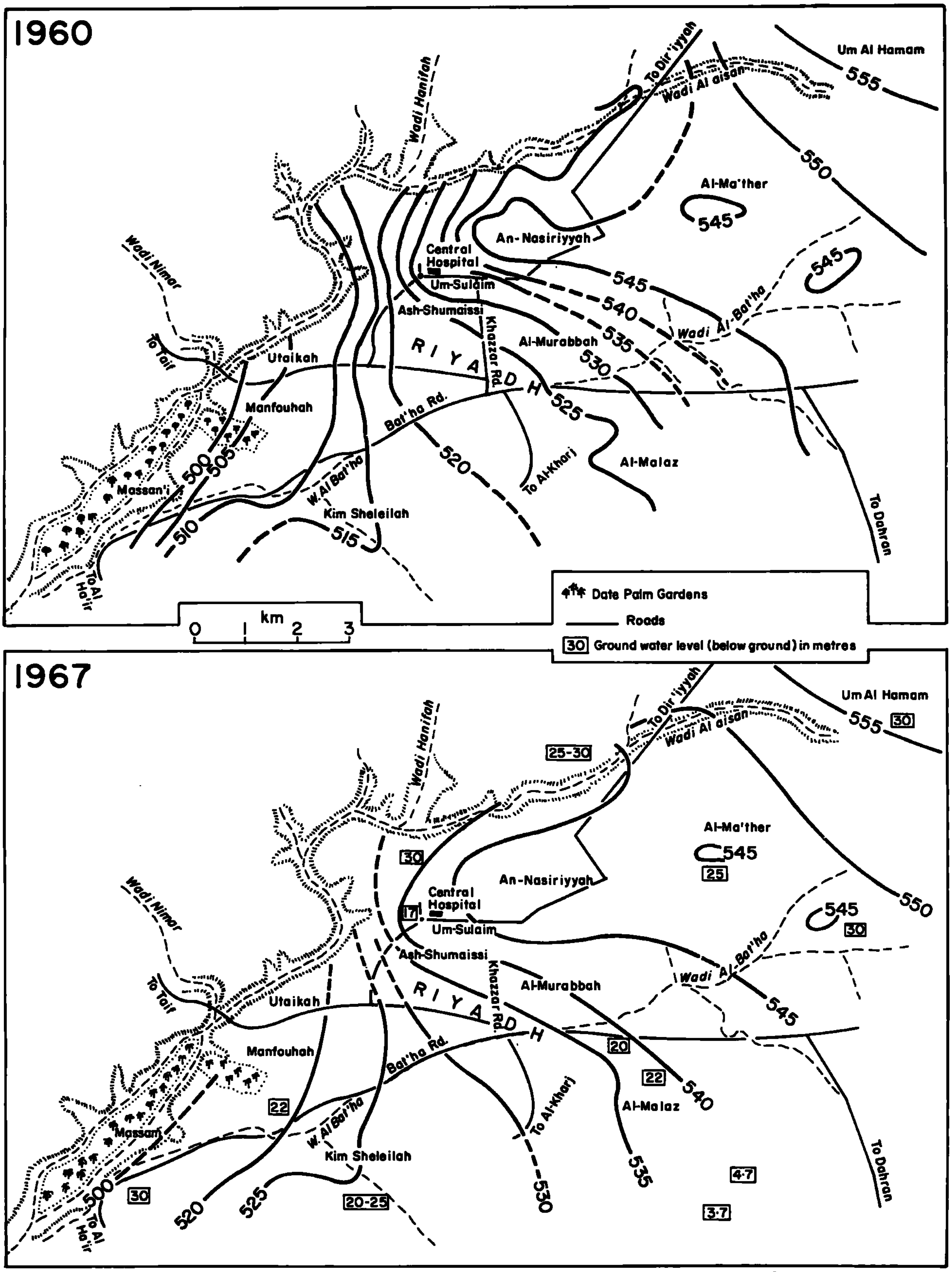
Alaisan, providing a substantial amount of water recharge.

8.2 Water Table Level and Water Table Flow

As a result of the continuous increase in the replenishment of the limestone by sewage water, the water table appears to show a considerable rise since 1956. Outside the city, particularly in the basin of the Wadi Alaisan, the depth of the water table ranges between 30 and 35 m beneath the ground. In comparison, the water table beneath the city ranges between 15 and 25 m, while in the southern suburbs - for example, Manfouhah and Al-Masan'i villages - the depth of the water table varies between 20 and 25 m. Prior to the recent expansion of the city, the water table over the whole extent of the Wadi Alaisan and Al-Bat'ha basins and in the area to the south was at more or less the same level. The constant replenishment of the Aquifer by the sewage water, caused the water level to rise between 10 and 12 m between 1960 and 1967. As the rate of pumping is less than the rate of recharge, the water table will rise gradually underneath the city, which will affect not only the underground water in the aquifer of the wadi alluvium deposits, but may also contaminate the reserve water stored in cement tanks, which are still used in almost every house in the city. The water circulates at a depth of between two and three metres with seepage directly from the pits; this phenomenon can be observed in the hilly areas of the western part of the city, particularly at Ash-Shumaissi (near the Central Hospital) and Um-Sulaim (between Al-Khazzan Street and the New Ash-Sumaissi Street). At some places within this stretch, the water falls about 1·5 m beneath the surface. It was previously thought, quite wrongly, that this circulating water was the water table of the Aquifer, whereas in fact the water circulates between the fractures as the rate of replenishment from the sewage pits is higher than the percolation rate of the limestone deposits. However, this subsurface water percolates slowly to the water table of the main Aquifer.

The direction of flow of the water has been affected by the recharge through seepage and by discharge in other parts. If we examine Figure 8.2A, we see that the direction of flow of the water appears to be from north to south, with an average gradient of 2·5 per thousand in the Wadi Alaisan basin in the north of the city. The disturbance caused by pumping in Al-Ma'ther and the upper reach of the Wadi Al-Bat'ha drainage has caused two minor local depressions. Beneath the capital city, the isopiezometric curve swings sharply toward the south where the farms and gardens of An-Nasiriyyah recharge the Aquifer with a comparatively large quantity of seepage water. This replenishment in the An-Nasiriyyah area increased in 1964 with the completion of building of the Royal Palace, the residence of the late King Saud. The effect of the water disposed of in An-Nasiriyyah diminishes gradually in the area between Al-Uraija and Al-Badi'ah, where the direction of the water flow becomes regular to the south of Ash-Shumaissi, with a gradient of 14 per thousand. In the area east of the Wadi Al-Bat'ha channel, the piezometric gradient is in the order of 7·5 per thousand, and in the lower part of the Wadi Al-Bat'ha, particularly near the tributary of Kim Sheleilah, pumping operations have affected the water table, characterised in curves 515 and 510. On the southern outskirts of Utaikah

Fig 8·2 PIEZOMETRIC MAPS OF THE WATER TABLE OF THE JUBAILAH LIMESTONE AQUIFER FOR 1960 and 1967



After: Sogreah 1967

and in the villages of Manfouhah and Al-Masan'i the water flow takes a south-westerly direction and emerges with the Wadi Hanifah alluvium aquifer.

When the piezometric level was again taken at the same location in 1967, it was found that the water level gradient in the Wadi Alaisan basin was more or less the same as in 1960 (Fig 8.2B). The local depressions at Al-Ma'ther and the upper Wadi Al-Bat'ha were still in evidence due to the pumping of local wells. The 'nose' of An-Nasiriyyah has expanded both westwards and eastwards as a result of the increasing use of water in the area, coupled with the construction of new houses all over the area. This has increased the water potential in the form of sewage pits, which still have a greater effect of infiltration than irrigation water, giving the local water table a gradient of 27 per thousand. In the area of Airport Street and Al-Malaz, the water table had risen by ten to 12 m, giving a piezometric gradient of about four per thousand. Near the tributary of Kim Sheleilah, the water table had risen more than ten metres as a result of a halt in pumping operations, and the seepage inflow of the city sewage. At Manfouhah and Al-Masan'i villages the water table is slightly higher than in 1960.

The continuous rise of the water table of the Jubaila Aquifer is unique in the Wadi Hanifah area. The problem here is pollution, which affects all the shallow aquifers within the Wadi Hanifah region. Such a rise in the amount of contaminated water will continue until the sewage pipeline project is completed. Thus, the danger of polluted water invading the alluvium aqifer is alarming. If we compare the water level in the main wadi channel and the adjacent Jubaila Aquifer, we see that the alluvium water has deteriorated over the last three decades, while the Jubaila Limestone Aquifer has risen considerably over the same period. As a result, the alluvium water to the west and south of the capital city has already been contaminated by the water transferred from the limestone.

8.3 Conditions of Discharge

The Jubaila Limestone Aquifer has been used for many decades; prior to the most recent developments which accompanied the growth of the city of Riyadh, the old hand-dug wells were scattered as far north as Um Al-Hamam on the Wadi Alaisan, and to the south of Manfouhah. The tapping of these supplies has differed from place to place according to water use. The old city was constructed on the west bank of the Wadi Al-Bat'ha, and formerly the city was flanked on all sides by palm grove gardens. As the area was mainly agricultural, small housing communities gathered near the old city, particularly in the southern vicinity, for example Jabrah and Salaam. In the eighteenth and nineteenth centuries, these small hamlets were no longer residential areas, and the land was taken over by irrigated farms (Al-Jasir, 1966). Thus the semi-trough of the Wadi Al-Bat'ha basin was made up of small cultivated areas, which got their water from the fractured limestone. The wells supplying the area struck water at an approximate depth of 15 m. As the cultivated gardens received their water from hand-dug wells, which were subject to replenishment, the gardens were rather small and thus numerous wells penetrated the Aquifer. In the old city, narrow, hand-dug wells scattered in the old streets are mainly concentrated near the larger houses and places of worship. Tapping the water of such wells is done by skin-pockets, which are operated by a single rope. Water from these wells was used for a variety of purposes, mainly cooking, laundry and for the ablutions required before prayers in accordance with Islamic tradition. Such wells have now been abandoned, due to the growth of the city and the installation of the water-pipe network. The old cultivated areas around the city have also been replaced by residential areas and parks. Accordingly, the present tapping is mainly for agricultural use outside the city, mostly in the basins of the Wadi Alaisan and the Wadi Al-Bat'ha.

The tapping of the Aquifer resulting from the recent wealth and increased prosperity of the city developed between 1950 and 1954, and during this period the introduction of mechanical drilling methods and turbine pumping helped to improve tapping operations. Other factors affecting tapping were the disappearance of the old agricultural gardens, swept away by the urban expansion around the city, and their replacement by new ones, either in use or deserted, and the attendant drilling of new boreholes. The urban explosion at the end of the 1950's brought about a considerable drop in tapping, not because of a lack of water reserves, but owing to the abandoning of the cultivated areas around the city. This was confirmed by comparing the amounts of water tapped in 1960 and 1967 (Table 8.1). In 1960, the total volume of water tapped was 410 l/s, while in 1967 it decreased to 350 l/s. According to Sogreah's survey, water from this Aquifer is tapped from 85 productive boreholes at various points over the extent of the Aquifer around greater Riyadh. The functions of these boreholes are defined as follows:-

TABLE 8.1

Water discharged from the Jubaila Limestone Aquifer in 1960 and 1967

Area	Water Extracted (i/s)	
	1960	1967
Al-Ma'ther	5	7
Kim Sheleilah	55	40
Wadi Alaisan	20	25
Um Al-Hamam	20	15
Al-Bat'ha upper reach	11	5
Al-Malaz	55	45
Other supplies	244	213
Total	410	350

Source : Sogreah, 1967

	Litres per Second
Riyadh Water Supply	120
Irrigation Use from Private Wells	200
Domestic Use from Private Wells	30
Total	350

However, both the quantity and quality of this water supply are inadequate for domestic needs, though sufficient for irrigation and street washing.

8.4 Water Quality

Samples taken from various points on the Aquifer showed that the original quality of water is better in places further away from urban districts, and this is also true of water extracted from the Jubaila limestone beneath or near the wadi alluvium. According to the samples taken by Sogreah in 1967 from 30 wells, the total dissolved solids appeared to be comparatively low and very similar to the total in the extreme northern area. This is mainly due to the origin of the water, which generally seeps from the flood accumulation and flow in the channels of the Wadis Alaisan and Al-Bat'ha. One exception is Well S 1011, west of the airport, which differs in chemical composition to the other wells in the basin.

The analysis of wells beneath the city of Riyadh has been affected to some extent by the sewage system of the city, which spreads over to the wadi alluvium aquifer in the west and south. Sixty per cent of the irrigation water of An-Nasiriyyah and Al-Ma'ther, which finds its way to the Jubaila Aquifer, is derived from the Minjur Aquifer. This, coupled with the sewage water taken from the Minjur water, has also largely affected the southern part of the Aquifer near Manfouhah village and Al-Masan'i, where the highest rates were recorded, particularly for nitrates (approximately 100 ppm). However, while this water finds its way through the cracks of the limestone, it shows irregularity in mixing with the original water produced by the run-off and lateral inflow from the wadis. It is now taken for granted that the aquifer beneath the city has already been contaminated, and consequently, the water in its sub-surface flow is mixing with the alluvium aquifer in various areas around the city, particularly west of An-Nasiriyyah, for example Borehole S 626, where the water contains 3,390 ppm of total dissolved solids. The Wadi Hanifah water in Al-Masan'i and Manfouhah gave the first warning; if the sewage water continues to percolate to the aquifer, in spite of the low rate of flow, the water in the wadi alluvium will be polluted, and this will eventually threaten the domestic water supply.

In comparison with the alluvium aquifer, water outside the greater Riyadh area shows higher mineralisation also. A well located 1km north-east of Al-Jubailah village penetrates the Jubaila Aquifer, and the water contains about 1,900 ppm of total dissolved solids (McCann, 1959). This will be representative of the quality of water in the limestone in the northern part of the Wadi Hanifah area. In addition, the water of the alluvium aquifer shows some change in chemical composition at various points near the bank of the channel (cf The Quality of Water, Chapter Seven).

In general, the water of the Jubaila Aquifer has relatively equal sulphate and chloride contents; its bicarbonate content is invariably lower; the rates of Ca, Mg and Na show considerable variation, and the

Mg rate is approximately midway between the Ca and Na rates (Sogreah, 1967).

CHAPTER NINE

MINJUR AQUIFER

The discovery of the Minjur Aquifer as a workable source of water is a consequence of the serious water shortage which faced the city of Riyadh in the early 1950's.

By 1953 geologists and experts in water management had been imported from the western world as well as from the neighbouring countries to give their views about tackling the problem of supplying the capital city with water. At that time the country lacked accurate knowledge of the geohydrological conditions, not only in Riyadh City or the Wadi Hanifah, but also all over the country. Because of its economic and political advantages, Riyadh City had become the destination of continuous waves of immigrants from outside as well as inside Saudi Arabia. The growth of the city to accommodate the newcomers and the establishment of governmental offices with new western standards forced the government to decide whether to divert all the water available in the Wadi Hanifah area to the capital, or to find a new source of water capable of meeting urban demands. The authorities realised that the first alternative was not practical, for it would have caused the cultivated gardens in the wadi area to vanish. Consequently, the city would have lost a major source of vegetables and fruit on the one hand, and would have been faced with yet more immigrants from the farms and villages of the wadi on the other. Furthermore, the government might have found it difficult to withstand the complaints of powerful farm owners and resistant peasants.

Consequently, the other alternative of searching for new sources of water has had to be put into effect. Despite the unsuccessful deepening of some existing wells, and the equally unsuccessful drilling of new boreholes to a reasonable depth, Camean (1953) warned that unless a new borehole were drilled to a maximum depth at the capital city to exploit all the water available downward, the problem would remain unsolved. Many separate investigations have followed, concentrating on the Wadi Hanifah catchment. One worth mentioning is the report submitted to the government of Saudi Arabia in January (1955) by the Hydraulique Afrique Company. The report gave a broad idea of the hydrological properties of the Riyadh region. Hope of a new workable aquifer was raised when a connection between the Minjur sandstone and upper Triassic in the Sahara was considered.

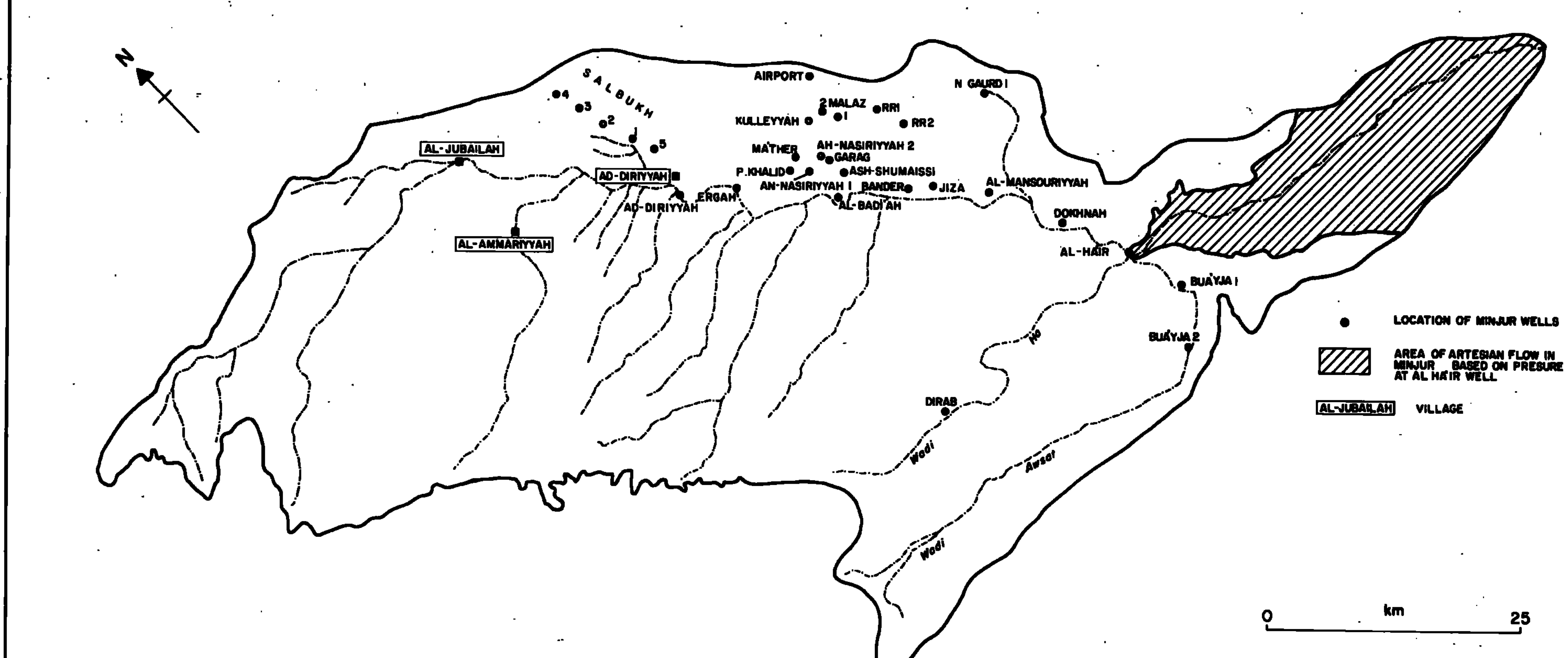
Thus, the comparison between the Minjur formation and a similar layer of sandstone belonging to the Triassic era in the Sahara, along with the results of previous investigations by various geologists, persuaded the water authority in the country to conclude an agreement with Hydraulique Afrique to continue work in the hope of striking fossil water. Eventually, that hope became fact when Ash-Shumaissi borehole was drilled and completed in the western part of Riyadh in 1956. Surprisingly, after the drilling had been completed to a depth of 1,307 m, the water rose to a level just below the ground surface. Pumping started in 1957 at Ash-Shumaissi well, and it was found that the well yielded 60 l/s, with a specific capacity of 2·3 l/s/m, and transmissibility of $3 \cdot 8 \times 10^{-3}$ m^2/s.

Following the success in tapping the Minjur Aquifer for water of drinkable quality in large quantities, underground water developments in the Wadi Hanifah region have concentrated heavily on the Aquifer. More than 25 boreholes have been drilled in the region since 1956. The well-field extends over an area with a radius of more than 30 km from Ash-Shumaissi borehole (Fig 9. 1).

The exploitation of the Minjur Aquifer has expanded as far as the region of Sudair to the north of the area under study, and the region of As-Sulayyel in the south (Quimpo, 1972). In 1972 about 50 boreholes in Saudi Arabia either penetrated or traversed the Aquifer. Twenty-one wells, at least, are within the region of Wadi Hanifah. Nevertheless, the exploitation of the Minjur Aquifer, unlike the shallow aquifers in the region, gives rise to many technical problems and high operating costs in terms of drilling and pumping. These factors throw light on the size and distribtuion of wells all over central Arabia. Naturally, the densest location is in the Wadi Hanifah region, and especially around Riyadh city.

However, the vast exploitation of the Minjur water in the Wadi Hanifah has caused a decline in the water level. This has caused alarm on account of two major risks. On the one hand, if the extraction remains within the relatively small area of the well-field in the region, then the risk of water depletion will be great. On the other, because the wadi region lies in the eastern part of the drinkable Minjur Aquifer, a shifting of the boundary between the salt and fresh water would be unpredictable (Aero Service Bahamas Limited, Sucursal Espanola, 1962). The fear of this danger encouraged the Ministry of Agriculture and Water in Saudi Arabia to sign a contract with the

Fig.9·1 LOCATIONS OF MINJUR WELLS IN THE WADI HANIFAH AREA



Sources: Sogrenh, 1967. Ministry of Agriculture and Water 1972.

consultant firm of McDonald and Partners in 1973 to investigate the further possibility of developing a new well-field in the Minjur Aquifer in the Al-Muzahimiyyah area, 60km west of the capital city. The contract also provides for an investigation of the Wasi'a Aquifer, 110km to the east of the city (Nouri, 1974). The Ministry of Agriculture and Water revealed in the Agricultural Guidance Bulletin (Vol 5, No 1, 1973) that the consultant company had agreed to undertake detailed geohydrological investigation, including the drilling of test wells. The firm was also to carry out a topographical survey of the area through which the proposed water pipeline will have to pass on its way to the city. The agreement also covers the economic and the technical side of the well-field operation.

The development of the Minjur Aquifer in the Wadi Hanifah and its surroundings aims mainly at meeting the municipal and housing demands of Riyadh City. The major question is whether the Aquifer can cope with these demands in coming years. Otkun (1970) estimated that the total reserve of Minjur water in the area 240 km south and 240 km north of the city was of the order of 2,010,000 x 10^6 cu m of water of a suitable quality. However, because of technical difficulties, the amount of water extractable is estimated at about 700,000 x 10 cu m. Considering the continuous growth of the city, owing to natural growth and immigration, coupled with an increase in the consumption of water per head, the Minjur is likely to supply the city with water for a few decades. The water authorities seem to be aware of the possibility of depleting the Aquifer. The Ministry of Agriculture and Water, which has the right to give permission to drill in the country, generally declines to allow private wells to penetrate the Aquifer within a radius of 50km around the city of Riyadh though a few exceptional private wells have been constructed within this radius, for example Al-Ma'ther well.

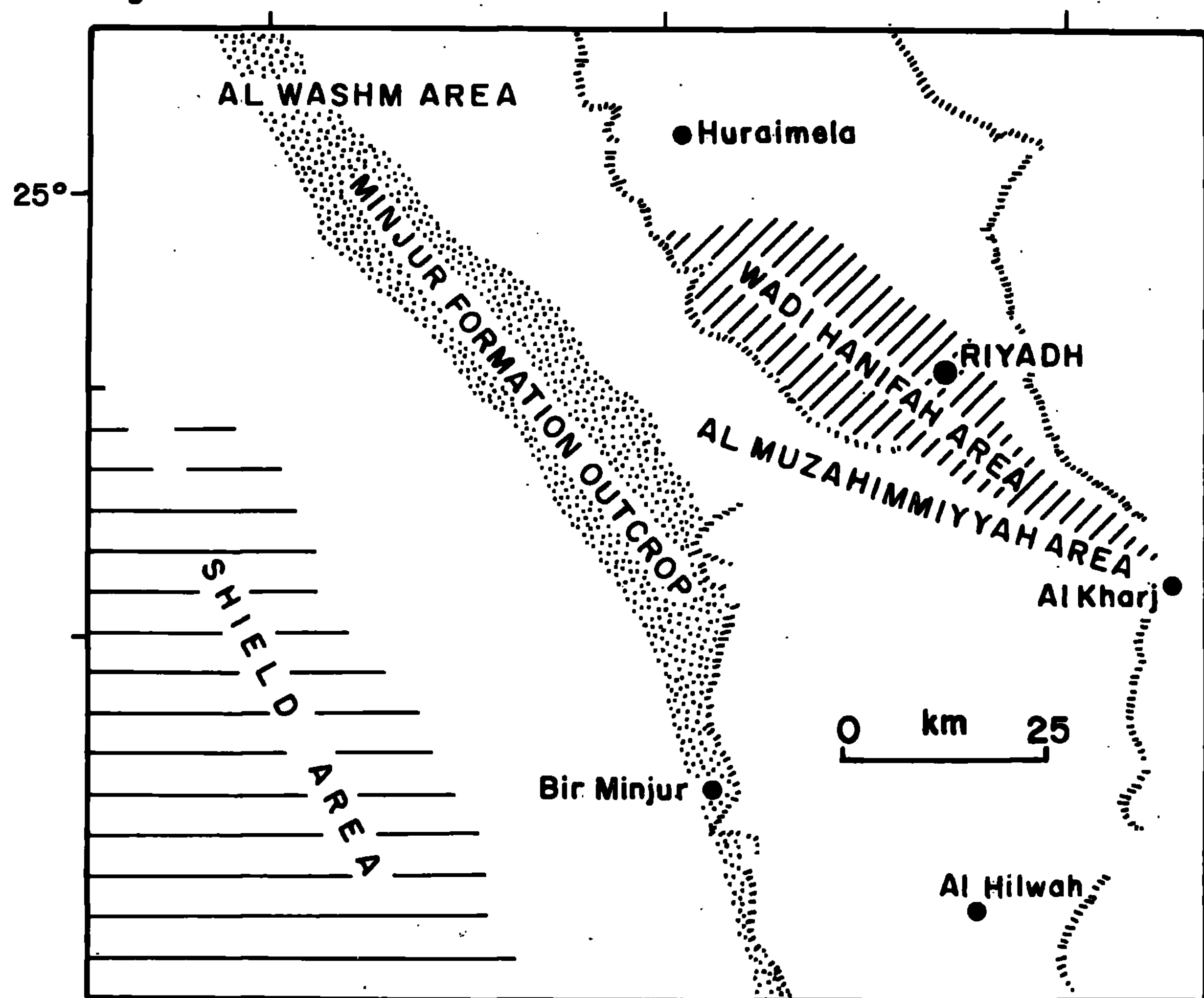
9.1 Geological Highlights

The Minjur sandstone exposes at the outcrop over an area of 6,500 sqkm. The outcrop lies about 75km to the west of the Wadi Hanifah proper (Fig 9.2) and extends 820km from north to south, between latitude 21° 32' N and 28° 07' N. Exposure is continuous except for some breaks in the extreme north and south.

The basic layers of the Minjur formation are in contact with the underlying Jilh formation, in which brown oolite calcarenite with marine fossil rocks are present in a type of cliff formation. Contact with the overlying Marrat formation seems to be unrecognisable near latitude 23°00' N due to the grading of the basal Marrat to sandstone. To the north the contact is between the maron siltstone and coloured sandstone of the Minjur and the grey, tan compact limestone of the basal Marrat.

The lithologic sequence of the Minjur formation constitutes a monotonous succession of light-coloured, cross-bedded, fairly coarse, consolidated, quartzitic sandstone, formed by the weathering of the old crystalline rocks of the Arabian Shield. The sandstone layers represent about 70% of the thickness of the whole formation. Ten per cent of the Minjur unit consists of varicoloured shale occurring at various levels in a thin bed which hardly exceeds 5 m thick (Powers

Fig 9·2. THE MINJUR OUTCROP



Source:-Modified from U.S. Geological Survey Map I-207A, 1958 et al, 1966). The rest of the formation consists of thin layers of conglomeratic material distributed through the entire formation, and including hard grey and brown limestone, dolometic cement and in some places gypsum .

The sand in the outcrop is white or light grey, weathering commonly to tan, red or yellow on account of oxidised iron. Some of the sand is cross-bedded, developed by the wind; in other places the deposits show a hydraulic origin. The effective grain size of the sand and the uniformity co-efficient vary from place to place vertically and horizontally through the Minjur sandstone. Sogreah (1968A) released data on samples taken at various depths from the Marat S38 borehole (Table 9.1), and the average on the results indicates that the permeability coefficient, calculated according to the formula of Allen-Hazen, would be $3\ 6 \times 10^{-4}$ m/sec.

Although an angular frosted quartz predominates, there is a host of feldspar in various degrees of alteration, hornblende and calcite, in addition to some igneous and metamorphic minerals in minor quantities. A few thin marine tongues of limestone in prominent outcrops were reported by Borwn and Lough (1963). Some thin beds of gypsum are exposed in association with the limestone near the basal layer of the formation. However, the Minjur sandstone is essentially non-marine of torrential eolian deposit. The other materials, limestone, shale and gypsum, of lacustrine origin might have been formed within inundated depressions.

Within the area between the Minjur outcrop and the Wadi Hanifah region, the formation is crossed by a network of continuous faults

TABLE 9.1

Samples taken from the Marat S38 Borehole

Sample taken from a Depth of (m)	Effective Grain Size (mm)	Uniformity Coefficient
39-111	0·20	2·75
111-129	0·14	3·20
129-144	0·16	3·10
195-201	0·20	3·00
225-234	0·40	3·80
243-255	0·30	2·20
267-273	0·21	2·90
276-282	0·35	3·40
303-312	0·22	2·50
Average	0·242	3

Source : Sogreah, 1968A

starting in the area to the west of Al-Majm'ah and Al-Artawiyyah (near latitude 26°30' N) and extending in a north-west - south-east direction to Al-Kharj plain (near latitude 24°13' N and longitude 47°10'E). Five grabens, bounded by the faults, have broken the strata of the Minjur unit. The most effective subsidence in the Minjur is the Dhruma graben. This graben extends over a distance of 60 km, and is approximately 1 or 2 km in width (Karpoff, 1955). The vertical displacement along the graben faults is of the order of ± 400 m. The Minjur formation in the collapsed zone is of similar or slightly greater dimension. The flow of water in the sandstone probably passes through the non-collapsed zone in a sinuous course between the grabens. On the other hand, some of the flow may also pass in the sandstone layers that occur at the contact between the Marrat and Jilh formations and the Minjur beds. Accordingly, although faults and grabens may entail some head losses of the flow, the Aquifer is not discontinuous.

The thickness of the formation varies from one place to another, particularly towards its northern and southern limits, presumably because the Minjur is disconformably truncated and overlapped by marine lower and middle Jurassic beds. The maximum thickness at the outcrop is found at Khashm Al-Khalta (latitude 23°35'24" N, longitude 46°10'36" E), where 315 m has been measured. To the south of Khashm Mawan (latitude 22°50' N), the formation diminishes rapidly and disappears near Wadi Ad-Dawasir. Thinning of the formation starts at Khashm Al-Khalta and continues northwards. A thickness of about 290 m was measured at Khashm Ad-Dhabi (latitude 24°13' N), and one of 185 m was also recorded north of Wadi Ar-Rummah (Powers et al, 1966). The range of thickness along the dip slope of the Minjur unit appears to vary from the outcrop in the west to the Khurais oil field in the east. Whereas the thickness at the Khurais oil field is 380 m, according to Brown and Lough (1963), the recent data taken from the Riyadh deep well (1968), which penetrated the entire depth of the formation, showed the total thickness to be 403 m. This means that the greatest thickness so far recorded is to be found in the region of the Wadi Hanifah.

From the hydrodynamic point of view, the sandstone in the base of overlying Marrat formation and the sandstone in the uppermost of the underlying Jilh formation are both related to the Minjur formation and constitute one single aquifer complex. Thus, in the area under study, the water-bearing sandstone is found, according to the log of the Riyadh deep well (1968), in two layers. First, the upper layer lies at a depth of 1,352 and 1,432 m and has a maximum thickness of 80 m. Second, the lower layer is located at a depth of between 1,570 m and 1,653 m. and has more or less the same thickness as the upper sandstone layer (Sogreah, 1968B). Almost all the boreholes drilled in the Wadi Hanifah region reached the upper layer of the Minjur sandstone. In most cases the boreholes did not penetrate more than 200 m into the Minjur unit.

9.2 Quantity and Quality of Water

Water in the Aquifer does not rely totally on the present annual rainfall. The commonly accepted idea is that the water reserved in the sandstone accumulated there during a period when conditions favoured precipitation. In recent years, more attention has been paid to the question of whether the formation receives any replenishment at the present time or not. Up-to-date information given by Otkun (1970) claimed that the percentage of recharge to the actual reserve is insignificant.

Nevertheless, in order to evaluate the recharge, if any, of the Aquifer, the prevailing local climate and the geological elements of the formation must be considered.

The outcrop itself extends in a belt from the north-west to the south-east, with a maximum width of about 33 km (near latitude 23°30' N), and a minimum at one point of less than 10 km (Powers et al, 1966). Topographically, the surface is rather flat, and consists of a buff and massive sandstone with irregularly distributed shale and shaley sandstone. In some places, particularly to the south of the Riyadh-Taif highway, small prominent features are scattered at some distance from each other, but these are too small to affect the local run-off. On the top, quite a large area of eolian sand is represented by Nafoud Kunaifethah, which extends about 300 km to the south of latitude 25° N. In addition, some surface deposits of silt, sand and gravel occur in some places located on and to the south of latitude 24° N (US Geological Survey, 1958).

The local climatic conditions are similar to those of the Wadi Hanifah area, combining low precipitation and high evaporation. Rainfall occurs almost from November through to May, but the rate of rainfall is lower than the rate in the Wadi Hanifah area. Climatological investigation revealed a decrease of rainfall to the immediate west of the Tuwaig mountain (Sogreah, 1968D). Thus, the mean annual rainfall on the Minjur outcrop was estimated at 75 mm.

The combination of a lower rate of rainfall and a permeable surface is unlikely to produce any important run-off, except where the compact Jilh formation (Triassic) and the Minjur outcrop meet on the surface. Here a local run-off, collected in small ponds, could be observed, notably near Khashm Musigirah on the Riyadh-Guway'iyyah road and at Khashm Midhya'ah further north. On the other hand, run-off does occur from the part of the catchment that extends over the neighbouring outcrop of the Marrat formation. A part of the relatively high run-off follows the initial slope from west to east, small wadis rise up on the west crest of the Marrat formation and flow eastwards through the Minjur sandy outcrop for a short distance. The length of these wadis does not exceed 10 km, and they dry up because of the permeability of the layers coupled with high evaporation. In the southern part of the formation, the extent of the outcrop is rather limited. Accordingly, the recharge is relatively low. At the Wadi Faw, Wadi Hinow and Wadi Al-Haddar, however, the Minjur formation is covered by an alluvium deposit favourable to contact infiltration. The infiltration effect on the Aquifer was confirmed by Sogreah (1968A) following an investigation conducted during the rainy seasons of 1966 and 1968 on two shallow wells in the outcrop.

It was observed that the level of water in the wells rose several metres after the rainfall (Table 9.2). Water analysis at the same time showed some improvement in quality, thus furnishing evidence that the rise

TABLE 9.2

Water Level and Water Quality of Bir Sidiriyyah and Bir Tabrak During the Rainy Seasons of 1966 and 1968

Well	Water Level Below Surface (metres)		T D S (ppm)	
	23.10.1966	16.5.1968	23.10.1966	16.5.1968
Bir Sidiriyyah	9	6	490	360
Bir Tabrak	16	4.15	1,100	800

Source : Sogreah (1968A)

of water level was the result of infiltration by the rain water and was not due to a decrease in the water extraction. Further results recorded the decline of the water levels in the shallow wells at the outcrop during the dry period when the water potential is usually insignificant. Thus the water penetrates slowly in the shallow perched aquifers at the depth reached by these wells, percolating either through the semi-permeable layers or by overspill from the perched aquifers.

With regard to the relationship between rainfall and infiltration, it was estimated that probably only 1·5% of the quantity of water in an average rainy year escapes evaporation and infiltrates to the Aquifer (Otkun, 1972). Taking this result into consideration as well as the average annual rainfall and the possibility of surface flow coming from neighbouring areas, the mean annual recharge of the Aquifer is about $0{\cdot}0015 \times 10^6$ cu m per sq km, which means the entire Aquifer receives annually about $9{\cdot}75 \times 10^6$ cu m.

Investigations carried out by the Ministry of Agriculture and Water as well as the consultant companies, to ascertain the total quantity of water in the Minjur sandstone, have produced conflicting estimates of the good-quality water reserve. Nevertheless, it seems clear that an accurate determination of the reserve in the Aquifer would require full investigations, including the following processes. First, the definition of the extent and nature of the Aquifer. Second, the discovery of the exact fresh-salt boundaries, both to avoid unnecessary drilling, and to predict possible salt-water invasion of the good-quality water zone. Unsuitable water needs to be located and eventually excluded, since the Minjur water is to be used for supplying domestic needs (Mishari, 1967).

Within the Minjur water, two different types of need require eventual satisfaction, the needs of (1) Riyadh water supply, and (2) the privately owned cultivated areas north and south of the Wadi Hanifah area. The satisfaction of the former seems certain, as the government is operating the extraction of the water whatever its depth. The satisfaction of the latter is doubtful because of the economic and technical difficulties which face the private sectors.

The Minjur formation varies in depth and thickness, as explained elsewhere. The combination of depth and dip goes with increasing salinity, which means broadly speaking that the salinity gradient is maximum in the vertical direction. Actually, allowance should be made for the unhomogeneous nature of the Aquifer. Following the drilling of Khurais well by Aramco (1960), about 150km east of Riyadh, it is known that the water there is saline and undrinkable. On the other hand, the traversing of the Minjur at Riyadh by many boreholes, shows that the water there is suitable for domestic utilisation. Accordingly, the boundary of saline water is somewhere between the region of Wadi Hanifah and Khurais.

Following various studies carried out by Sogreah from 1966 onwards, it is found that the salinity of the water decreases eastwards corresponding to the depth of the Aquifer. A test of four boreholes (Table 9.3) between the outcrop and the identified saline zone (Khurais) proved that the water above 500 m beneath sea level is of good quality, which means that the eastern boundary of the Wadi Hanifah region is roughly the same as the fresh-water boundary. Allowing a reasonable margin, the depth of 1,000 m beneath sea level is considered to be the

TABLE 9.3

Volume of Stored Water in Minjur Formation

Section (Reference : Sea Level)		Volume (10^6 cu m)		Total Volume Stored * (10^6 cu m)	TDS (ppm)
From (m)	To (m)	Non-Exploitable Reserve	Exploitable Reserve		
+750	0	500,000	250,000	750,000	1,200
0	-500	420,000	210,000	630,000	1,300
-500	-1,000	420,000	210,000	630,000	2,000

* Stored water expected in the clayey layers is excluded. (Based on Sogreah data, 1968A)

absolute boundary of the Minjur's usable water.

The area up to 100km eastwards from the outcrop is considered to have more or less drinkable water. Bearing in mind the extent of the Aquifer and assuming the porosity ranges around 30%, the volume of water reserved in the Aquifer is as much as 2,010,000 x 10^6 cu m. (see Table 9.3).

In reality this amount of water cannot be exploited since part of the water is retained in the ground. The quantity of water which could actually be obtained is dependent on the effective porosity which was assumed in Minjur to be 10% in the sand and sandstone of the Aquifer (Sogreah, 1967). As a result, the amount of water which can be extracted is estimated to be approximately 670,000 x 10^6 cu m. Moreover, an additional quantity of water must be reserved in the interbedded clayey layers of the formation. Owing to the need for more investigation, it is too early to estimate the amount.

It has been revealed that the intention is to keep the Minjur water for the urban demand of Riyadh City. As for the volume of water suited to urban demand, samples collected confirmed variation in the water quality according to locality and depth. In the Wadi Hanifah area where numerous wells penetrate to the Aquifer at different depths, the amount of total dissolved solids varies from one well to another within a range of between 1,100 and 1,500 ppm. The sodium chloride content increases within the depth of the Aquifer, which may be a result of the slow flow of water in the lower beds. Samples taken within two categories of wells in terms of depth indicate that sodium and calcium sulphate are the major chemical deposits in wells that penetrate into the Minjur sandstone at a depth of less than 170 m. The wells of Ad-Dir'iyyah, Al-Kulleyyah, Dukhnah and Al-Badi'ah lie within this category. Samples collected from the wells of An-Nasiriyyah, Ash-Shumaissi and National Guard No 1, whose depth in the Minjur exceeds 170 m, showed that the main content is calcium sulphate and sodium chloride. Therefore, a borehole which penetrates the Aquifer to a small depth is likely to have water of relatively good quality. However, the oldest well, Ash-Shumaissi, has tended in recent years to show an increase in salinity, and this may prove true of the other operating wells as pumping increasingly continues. However, the water in Riyadh City is treated before it is contributed to the municipal supply.

In A-Muzahimiyyah, from whose wells the Minjur water will be piped to Riyadh, the quality of water is questionable. Samples taken from the well S430 confirmed that the water is of bad quality. The Ca, HCO_3, Mg and SO_4 ion contents are very low; while the NaCl ion is the main content (Sogreah, 1968A). No possible explanation could be obtained for this, except that the water composition is affected by the faults of Dhruma graben in the north and the fault semi-continuation of Al-Awsat in the south.

The age of the water in the Minjur Aquifer in the area of the Wadi Hanifah is believed to be more than 25,000 years. This conclusion was arrived at by testing three wells near the gravity centre and the fringe, i.e., Ash-Shumaissi, Al-Ha'ir and Jiza (Otkun, 1972). The age of the water in the Ash-Shumaissi borehole was claimed by Quimbo (1972)[2] to be 24,630 ± 500 years. Others thought the age of the water in some areas was about 30,000 years (Nouri, 1974).

9.3 Conditions of Discharge and Water Level

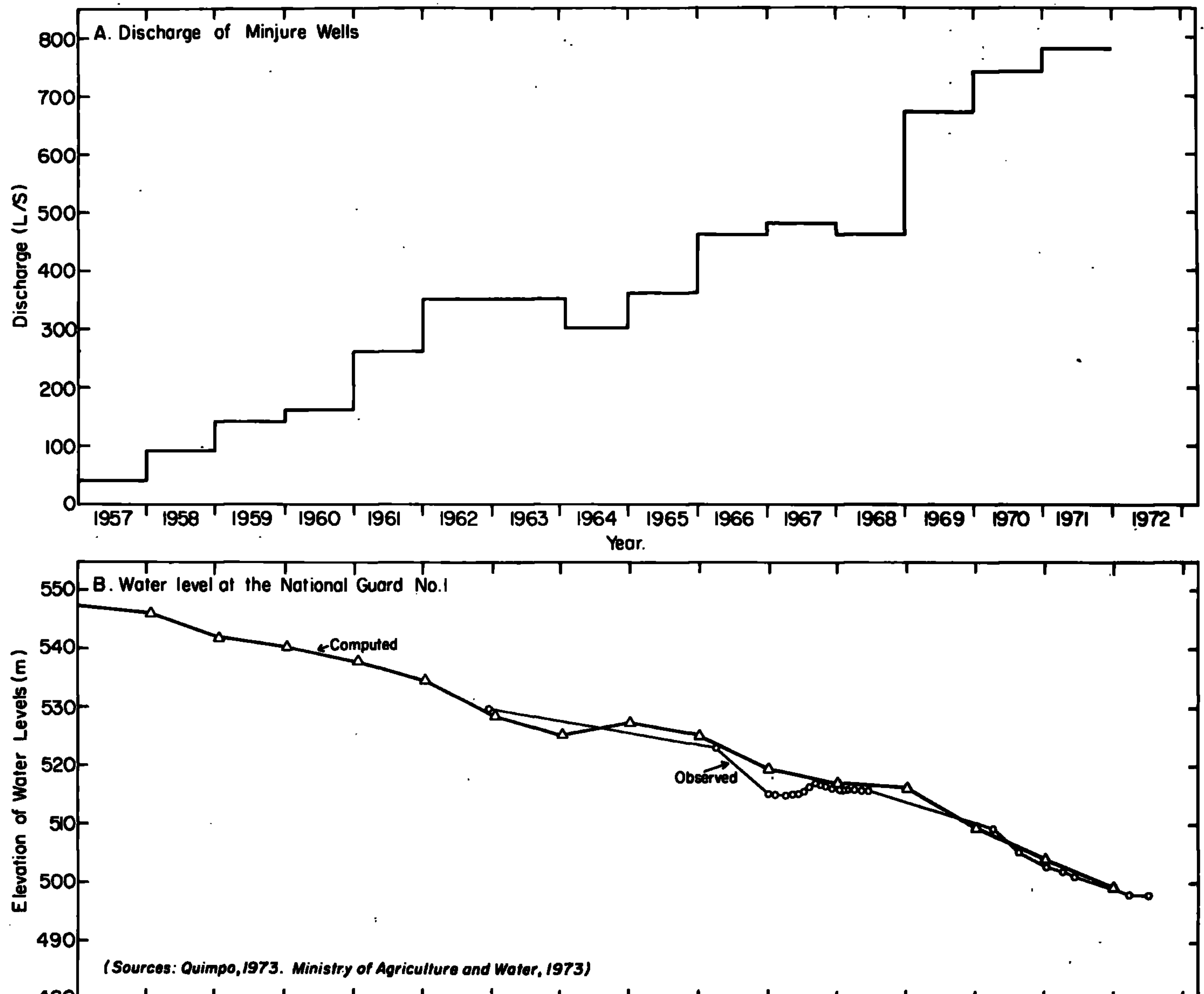
When the first well of Minjur was drilled and completed on the 10th October 1956, the log showed that the total depth was 1,807 m and the static water level was 84·75 m beneath the surface. Following that event, 15 wells were completed in the Wadi Hanifah area in a period of five years, eight of them within a radius of 8 km around the Ash-Shumaissi well. Exploitation accelerated sharply from 1960 onwards.

Since the Aquifer recharge is relatively insignificant and the rate of flow is very slow, a lowering of the water table in the Wadi Hanifah region resulted from the increasing discharge. Between the start of the pumping in Ash-Shumaissi well (1957) and February 1960 the static water level in the well had declined by 13 m. During the same period, four other wells were put into operation at different times, and the total mean discharge was nearly 160 1/s.

The record of August 1960 confirmed that the rate of decline continued to be more or less the same. Observations taken on 30th October 1962 showed that the following 18 months saw a drop in the piezometric level from 521·5 to 513 m. No record of the amount of water drawn from the wells was available, but it was evident that in 1962 the mean discharge of all wells was about 300 l/s (Fig 9.3). Following that period, from 1963 to 1965 there was some decline in the quantity of water extracted from the Minjur wells. Consequently, the water level became relatively stabilised.

Though the water extraction increased by more than 400 1/s in 1966, it again tended to stabilise in the three following

Fig 9·3 Discharge and water level in the Minjure Aquifer Wadi Hanifah Area (1957-1972)



years. Relative to the rapid growth of domestic needs, the water consumption has increased gradually, which means that another source of water has also been used from time to time. The added water must be from the shallow aquifers within the region, particularly the wadi alluvium wells. No available records back this hypothesis, but it is probable, since the water from the shallow aquifers is easily obtained, either by raising water or through their supply to the three main reservoirs, which in turn supply water to the city of Riyadh. The availability of ground water in the wells of the shallow aquifers can be concluded from the rainfall data in the region. Accordingly, whenever the amount and density of rainfall is comparatively high, the discharge from the Minjur wells decreases or stabilises. One clear example is that, while the total rainfall in the year 1963-1964 (from November to October) at Riyadh Airport was 104·4 mm, in one day the amount of rainfall was recorded to be from 40 to 50 mm. With such density of rainfall, the run-off must have been quite high. The consequent flood, except for the evapotranspirated water, would infiltrate through the alluvium deposit. In addition, the possibility of conserving water by careful handling and special projects could be considered.

However, the vast demand for the water and the continuous drilling of more wells caused the yield of water to increase from 1966 onwards. At the beginning of 1972, the mean yield of the National Guard Well No 1 was about 800 l/s, and the observed water level had dropped by about 32 m in a period of ten years' time (Fig 9.3.).

Because of the lack of investigation into the characteristics of the

Aquifer in consequence of its recent discovery, the piezometric level was not at first known. The first attempt to measure it was made at the end of 1962, when observation of 15 wells showed a continuous water decline. On 6th October a suggestion was made that all the existing wells should stop operating for 24 hours to permit the water in the wells to rise (Brown and Lough, 1963). The suggestion was put into effect on the 29th and 30th October in that year. All well pumps were turned off for 24 hours, after which it became necessary to start pumping again. It was noticed after the observation that the water-levels in the wells in the gravity centre of the well-field were still rising, while the water level on the fringe of the well-field had reached a static level. The results showed that the water level at Al-Ha'ir well in the southern part of the well-field was 1,752 ft (533·31 m) and in Ad-Dir'iyyah well the water surface rose to 1,664 ft (502 m), while at Ash-Shumaissi well in the centre, the piezometric surface was 1,684 ft (505·28 m). The general core of depression reflected withdrawal from storage and, despite the general downward slope of the Aquifer towards the east, the general ground water movement appeared to be from south to north (Brown and Lough, 1963), perhaps as a consequence of the extraction depression. These results gave a broad idea of the exact piezometric gradient, but they did not rule out the possibility of error in terms of water temperature and variety of salinity.

Thus, in order to determine the piezometric level of the Minjur water, two factors have to be considered. On the one hand, when measurement was carried out in the Wadi Hanifah region, it was found that the water temperature was slightly high, averaging 52°C. When the piezometric level was measured immediately after pumping, an exaggerated level occurred, owing to the expansion of the water column. When the measurement was repeated after the temperature of the water had dropped, the water column, which was about 1,200 m high, had decreased by approximately 2 m (Otkun, 1972). On the other hand, it was found that, according to the various grades of the salinity of the water in the entire Aquifer, the piezometric level would be liable to an error of one metre in a column 1,200 m high. However. the deleted error in the piezometric level caused by salinity and temperature is restricted to the Wadi Hanifah area. The remaining wells in the Aquifer have not been fully tested, but the error presumably increases from the west to the east, as indicated by the corresponding increase in salinity and temperature. The measurements and data were collected mainly from the existing boreholes which are concentrated in the Wadi Hanifah area, while wells in other regions are scattered and need more observation.

The depth of the piezometric level in the Wadi Hanifah region varies according to the elevation of the ground. In the northern part of the well-field, where the altitidue is slightly high, the depth of the water level at Ergah well in 1967 was about 118 m below the surface of the ground, while in the National Guard well No 2 to the east of the region, the water level was 60 m below the surface of the ground. In the southern part, at Al-Ha'ir in particular, the Aquifer had an artesian flow on the ground surface.

From the available data and observation, it is assumed that the Minjur Aquifer becomes artesian in the lower Wadi Hanifah area; in other words, from Al-Ha'ir village southwards, except for a small area where the relief contour lines are more than 530 m (see Figure 9.1). However, this rule will not apply for long if the amount of water extracted from the wells continues to increase as it is. In other words, until the Aquifer under the Wadi Hanifah area reaches an equilibrium where the water moving underground equals production, the decline of the water table will be progressive. The acceleration of the exploitation which started in 1957 has caused a depression in the aquifer beneath Riyadh City. All wells are concentrated within a radius of 32 km around Ash-Shumaissi borehole. Seven wells are owned privately and their pumping lasts a few hours a day. The remaining boreholes are pumped 24 hours a day with a high yield, unless the pumps need servicing or have been damaged. Such conditions have caused a heavy fall in the piezometric level noticeable not only in the gravity centre but also for as far as 70 km in all directions.

The National Guard well No 1, which has never been pumped since it was completed, showed a clear idea of the piezometric decrease. The well is located near the Riyadh - Kharj road, about 16 km to the east of Ash-Shumaissi well. From the data obtained, the piezometric level fell by 32 m from 1962 to 1972.

In the case of wells pumped regularly at a high yield, a very large drop in the piezometric level is observed in the first years of pumping. The decline was over 25 m a year in Ad-Dir'iyyah well during the first two years of pumping (Fig 9.4). According to Davis (1959A), it was also noticed that when a new borehole had been drilled, the piezometric level was lower than the original level of the previous one, which reflected

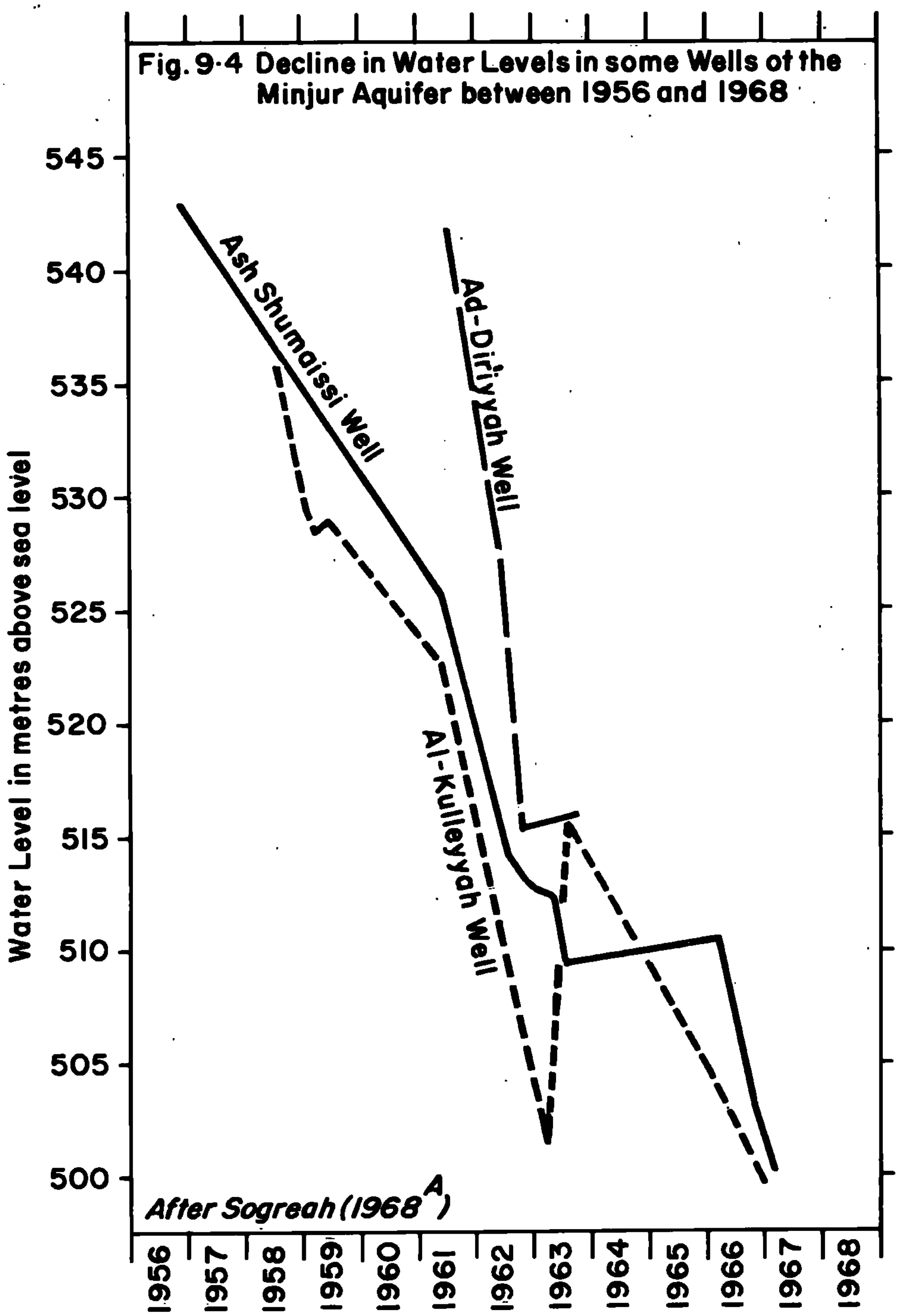


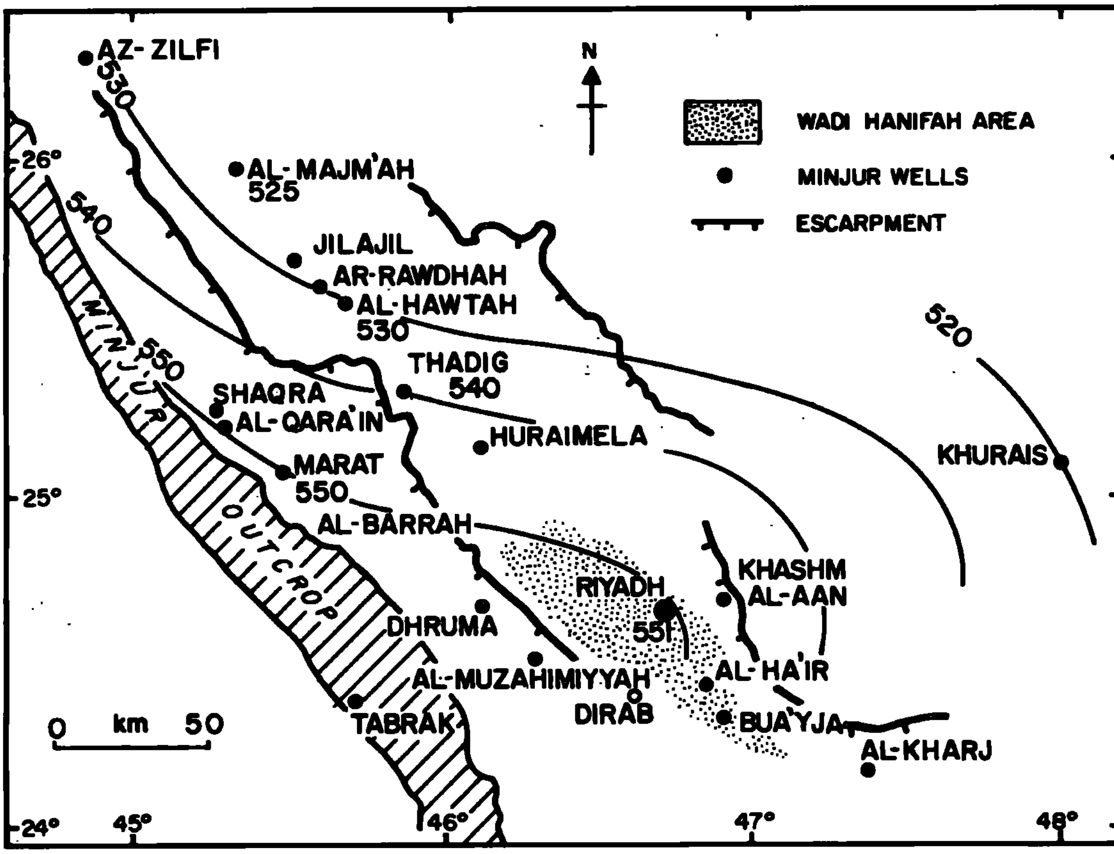
Fig. 9·4 Decline in Water Levels in some Wells of the Minjur Aquifer between 1956 and 1968 the interference to the water level caused by the existing wells.

However, in the Minjur wells of the Wadi Hanifah region, many difficulties impede the measurement of the water level. In addition to the salinity and temperature exaggeration, the pumping of wells is intermittent, either because a particular well is private and therefore only operated for a few hours a day, or because a pump needs servicing, which may prevent its operating for one or two months. Furthermore, it was noticed that the rate of discharge is bigger after the pump is serviced and becomes smaller as the pump wears out. (Quimpo, 1972).

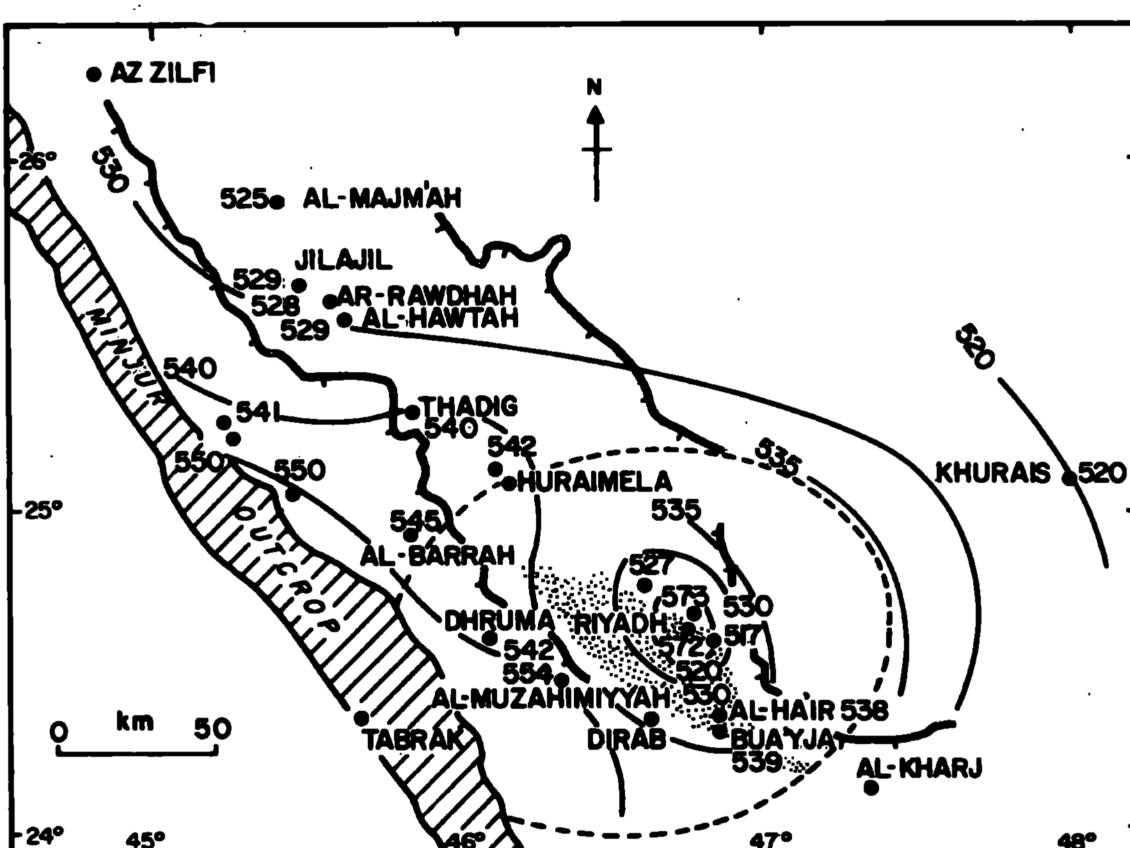
In order to evaluate the depth of piezometric level, it was assumed that as the Minjur Aquifer is hydraulically connected, it would be more efficient to give a piezometric gradient for the entire Aquifer, and specifically between the unconfined section of the Aquifer and the Khurais area. Because the formation had not been investigated prior to the extraction of the confined Aquifer, the first attempt was carried out by Sogreah in 1967 using measurements taken immediately after the completion of the drilling of Ash-Shumaissi borehole in 1956 and of the Khurais borehole No 1 in 1958, the latter being beyond the fresh-salt water boundary. The measurements were taken in 1965 in the Sudair area a distance of about 100km towards the northern boundaries of Wadi Hanifah region. And finally the evaluation was based on two wells in the unconfined Aquifer - Bir Tabrak, 90km west of Riyadh, and Bir Minjur, about 120km to the south-west of Riyadh. The tentative piezometric map (Fig 9.5A) showed the existence of a piezometric gradient from the Minjur outcrop area tending east-north-east and north of the line between Khurais and

Fig 9·5 PIEZOMETRIC MAPS OF THE MINJUR AQUIFER

A PROBABLE PIEZOMETRIC MAP OF MINJUR AQUIFER BEFORE PUMPING



B PIEZOMETRIC MAP IN 1966-67



Source: SOGREAH (1968 A)

Riyadh. It was also concluded that, because the Aquifer becomes thinner towards the north-east, the gradient must in consequence be relatively steeper. The nose of the piezometric lines along Riyadh-Khurais goes with the isopach lines of the formation and faces the zone where re-charge appears to be greater due to the extent of the Aquifer coupled with the height of the infiltration rate.

The measurements taken recently showed the super-imposition of a large depression on the initial piezometric surface due to the heavy density of wells in the Wadi Hanifah area. The fall in the piezometric surface decreased in all directions and influenced the elevations of the water level outside the Wadi Hanifah region.

Comparing the Figures 9.4A and B, we see that the iso-piezometric lines 540 and 550 m in 1966-67 get close to each other in the graben zone south-west of the Wadi Hanifah area owing to the dam effect of the Dhruma Graben, which creates head losses in the ground water flow coinciding with the seepage flow resulting from water drawn off in the area under study.

CONCLUSION

Being situated in an arid land, where surface water is absent except for a few hours a day after torrential rain, the urban and agricultural settlements in the Wadi Hanifah area are totally dependent on the ground water supply. Prior to the discovery of oil and the resulting recent wealth of the country, the Wadi used to be typical of the settlement centres in central Arabia. The population was largely concentrated in limited areas which were mostly distinguished by access to ground water. The prevalence of such small, scattered settlements made it evident that the water shortage was the greatest obstacle facing the life of the region.

Water in the region is governed by both the volume of rainfall and the lithology and the type of geological formation. The area is characterised by the drainage of the wadi dissecting the surface exposures of the Upper Jurassic and Early Cretaceous.

Ground water is retained in three aquifers:-

(1) in the wadi alluvium deposit, which receives its water from direct infiltration following rainfall.

(2) in the joints and cavities of the Jubaila limestone; mainly in the upper portion of the unit.

(3) in the Minjur deep sandstone.

The remaining geological units appeared to be non-water-bearing series as confirmed by the Riyadh deep well in 1968. Thus, they are excluded from this study.

Prior to the later change of economic and social standards, flood that had accumulated in the wadi channel used to be applied, for a short period, to irrigation. Afterwards, the shallow ground water would be utilised in a minimal way. Over the years, experience of how to benefit from the shallow aquifers led to the maintenance of a balance between recharge and discharge.

The Alluvium Aquifer used to supply the rural areas along the whole length of the wadi. The water level ranged between a few metres beneath the surface in the rainy season and not more than 30 m in the dry season. The Jubaila Aquifer used to be the main supply for the city of Riyadh and its surroundings. At that time, water development and exploitation techniques were relatively simple, mainly hand-dug wells within a shallow depth operated by very simple lifting devices.

A change in that traditional system started to take place soon after the establishment of the Kingdom of Saudi Arabia. The oil revenue which was introduced shortly afterwards has enabled the change to take place.

As the city of Riyadh was chosen to be the capital of the country, its fast expansion resulted in two things. First, many cultivated areas in the vicinity were replaced by urbanisation. Second, the growth of the city imposed an urgent need for more water for both building and domestic purposes.

As a result, the traditional methods of lifting water appeared to be too slow to cope with the sharp increase in water consumption. In addition, the new prosperity, which the country had never enjoyed before, necessitated a dramatic change in water development as well as other aspects of life.

Thus, foreign experts and modern technology were introduced to the region. Modern equipment was used to pump water from the Jubaila Aquifer. Then, it was realised that water in the existing hand-dug wells was no longer sufficient for a year-round supply.

As the geological units and their hydrological properties had not been investigated, drilling seemed to be the only way to locate new sources of water. Although a few boreholes were drilled to a considerable depth, no additional water was to be found. Thus, deepening and exploitation accelerated and the water level deteriorated sharply.

Although no record of the water level in the Jubaila Aquifer could be traced, the drilling of the Alluvium Aquifer at the Wadis Liban, Nimar and Al-Ha'ir in the early 1950's gave evidence that the Jubaila Aquifer had been over-exploited and depleted.

The government then began to use new technical methods for pumping in the Alluvium Aquifer, and farmers in various villages along the wadi course were also indirectly encouraged to do so. As the traditional raising of water by animals continued to diminish, new pumps were set up instead. The large market for vegetables and fruit at nearby Riyadh gave reasonable incomes which were invested in deepening and drilling.

Owing to the absence of water legislation and control, the traditional water table had dropped badly; and many boreholes dried up.

As the capital city was growing fast, existing water in both the Jubaila Aquifer and the Alluvium could not satisfy the large demand. Consequently, other solutions were investigated, but without success.

Then, water development concentrated on two combined objects:-

1) to attempt to increase water recharge in the alluvium;

2) to explore for more water in the underlying units.

Thus, a number of dams were constructed on the wadis near the capital city. This clearly indicated that the prime purpose was to increase recharge for the Riyadh water supply boreholes at the wadis Liban, Nimar and the wadi proper. Other areas, such as Ad-Dir'iyyah and Irgah, where water supplies had deteriorated, were not given consideration.

Owing to the fact that this solution was not based on an overal investigation, some problems arose. Before the building of dams, flood used to flow along the wadi course. Dams therefore obstructed the traditional recharge of one of the cultivated areas in the wadi between the Wadi Hanifah Dam and Al-Ha'ir. In the meantime, the fine silt deposit laid in the dams decreased the infiltration and also helped more water to be wasted by evaporation. It could be argued, however, that these dams are too small to obstruct any major flood. Although ideally this is so, flood does not always occur in the whole wadi, owing to the basin characteristics and the precipitation regime.

Contrary to the shallow aquifers, the Minjur Aquifer had a substantial volume of water when first exploited in 1956. Water has been raised up to the surface from a depth of more than 1,000 m. Again modern technological methods helped to depress the water level. Within a few years of the beginning of extraction, the Aquifer was penetrated by a number of deep wells concentrated in a relatively small area. At this well-field, the water level has been lowered by more than 50 m since the first drilling. As a result, problems of salinity and expense have arisen.

As a consequence of the high rate of utilisation from the Minjur Aquifer, combined with the absence of an adequate sewerage system, sewage water found its way down to the Jubaila Aquifer. This Aquifer, which had been almost depleted in the early days of pumping, started to rise up again in proportion to the amount of water used in the city and its surroundings. In the meantime, the Aquifer continued to receive the natural recharge of the Wadis Alaisan and Al-Bat'ha. The water in the Aquifer has now become so polluted that it is almost out of use. Moreover, the contaminated water in the unit is affecting the adjacent section of the Alluvium deposits.

The preceding remarks show that water resources in the Wadi Hanifah have suffered greatly from a lack of control and from improper management.

In the first period of development, ground water was treated as though it was an independent resource. When the need for control arose, the lack of adequate major investigation was reflected in the disappointing results. Since agriculture is as important as other types of water use, the shallow aquifer cannot be, at present, an adequate source of supply.

Again, in the urban sector, the water wastage by both the private consumer and the authority is an alarming factor. Various authorities deal with water in the region. The Ministry of Agriculture and Water is responsible for estimating the quality and quantity of water required, and for finding, storing and treating it. The Riyadh Water Board is responsible for delivering it, while the Municipalities Ministry tends to be in charge of water sewage projects. As the three authorities are administratively separate, each one deals with its responsibility in the manner and time considered to be proper. This may throw light on water conditions as they exist today.

However, as the country is still undergoing its first experience of development, with a shortage of skilled and technical staff, such problems seem to be unavoidable. This is especially so since the bulk of previous investigations were carried out by foreign firms, which all too often had no prior experience of the social and economic aspects of the country.

In recent years, water development has tended to improve, yet water management and planning still need more organisation.

The point which has to be raised is : will the wadi region be able to satisfy the demands for water? Although no absolute answer can be given at the present time, the future seems to be rather gloomy. However, water in the Alluvium Aquifer will be available in the upper reach of the wadi and in the lower reach, where water has not yet been over-depleted. The Minjur Aquifer will be able partially to supply the municipal demand. Yet, difficulties of salinity and technical operations could be major obstacles.

Water control and treatment are urgently necessary to relieve the situation. In addition, water projects always need to be investigated in relation to the master plan of the country. In doing so, a fair share of utilisation as well as proper planning can be achieved.

Finally, it is hoped that this study will shed light on the water resources not only in the study area but also in the rest of the country.

BIBLIOGRAPHY

I - Used Bibliography

(1) Abdul-Ela, M.T. (1965 A) "Some Geographical Aspects of Al-Riyadh". Bull. Soc. Geogr. Egypt. Vol. 38 pp 31-72.

(2) ------------- (1965 B) "Geography of the Arabian Peninsula". Dar Al-Bayan, Cairo. (in Arabic)

(3) Aero Service Bahamas Ltd. Sucursal Espanola (1962) "Resistivity Surveys in Saudi Arabia". Unpublished Report filed in the Central Planning Organisation, Riyadh.

(4) Al-Abdul-Razzaq, F. (1971) "The Problem of Water in Kuwait". M.A. Thesis, Geography Department. University of Cairo, Egypt. (in Arabic)

(5) Al-Humawi, Y. (1955) "Description of Places". Dar Sadir, Beirut, 1955, (in Arabic)

(6) Al-Jasir, H. (1966) "History of Riyadh City". Dar Al-Yamamah, Riyadh, (in Arabic)

(7) Aramco (1948) "Water Supply for Riyadh". A Report prepared for the Government of Saudi Arabia, Riyadh, 1948.

(8) ------------ (nc date) "Geological Reconnaisance of Kharj Area and surroundings including parts of Riyadh, Hauta and Wasia Quadrangles". Report No. G. 27

(9) Biel, E.R. (1946) "Climatology of the Mediterranean Area". Publication of the Institute of Meteorology of the University of Chicago, Chicago Press.

(10) Brown, G.F. (1949) "Geology and Ground Water of Al-Kharj District, Nejd, Saudi Arabia". Ph.D. Thesis Northwestern University, Evanston, Illoinois.

(11) Brown, G.F. (1950) "The Water Supply for Riyadh". A Report prepared for the Ministry of Agriculture. U.S. Geological Mission, Riyadh.

(12) Brown, G.F. and Lough, C.F. (1963) "Water Supply for Riyadh, Saudi Arabia". Unpublished Report prepared for the Ministry of Agriculture, Washington, 1963.

(13) Consulted Limited (1971) "City of Riyadh Sanitary Sewerage Master Plan". Unpublished Report prepared for the Ministry of Interior, Riyadh.

(14) Davis, R. (1959) "Upper Wadi Hanifah Water Resources". Unpublished Report prepared for the Ministry of Agriculture. Ralf M. Parsons, Engineering Co., Riyadh.

(15) Davis S.R. (1959 A) "Review of Wadi Hanifah Water Resources". Unpublished Report prepared for the Ministry of Agriculture, Riyadh.

(16) -------------- (1959 B) "Addendum Review of Wadi Hanifah Water Resources". Unpublished Report prepared for the Ministry of Agriculture, Riyadh.

(17) De Wiest, R.T. (1965) "Geohydrology". John Wiley & Sons, Inc., New York, London, Sydney.

(18) Fisher, W.B. (1971) "The Middle East". Methuen & Co. Ltd., London.

(19) Flint, R.F. and Skinner, B.J. (1974) "Physical Geology". John Wiley & Sons, Inc., New York, London, Sydney, Toronto.

(20) Freeman-Greniville, G.S.P. (1963) "The Muslim and Christian Calendar". Oxford University Press.

(21) Govenco Company (1954) "Riyadh Reservoir and Hayer Pipeline". Unpublished Report prepared for the Ministry of Agriculture, Riyadh.

(22) Hydrology Department (1973) "Infiltration in Hanifah Dam Reservoir and Wadi Hanifah Reach-Between Hanifah Dam and Ha'ir Bridge". Unpublished Report filed in Hydrology Department, Ministry of Agriculture and Water, Riyadh.

(23) Hydrology Department (1973) "Behaviour of Wadi Hanifah Dam and its Reservoir". Unpublished Report filed in the Hydrology Department, Ministry of Agriculture and Water, Riyadh.

(24) Ibn Bishr (1971) "The Guide of Pride in the History of Nejd" Dar Al-Yamamah, Riyadh, (in Arabic)

(25) Ibn Eissa (1966) "History of Some Events Occured in Nejd Between 700 and 1340 A.H.". Dar Al-Yamamah Riyadh, (in Arabic)

(26) International Bachtel Inc., (1951) "Sub-surface Dam at Riyadh". Unpublished Report prepared for the Government of Saudi Arabia, Riyadh.

(27) Karpoff, R. (1955) "Etude Geologique De La Region De Riyadh". Unpublished Report prepared for the Ministry of Agriculture. Hydraulique Afrique, Paris, (in French)

(28) Leachman, G. (1914) "A Journey through Central Arabia". Geog. J., Vol. 43, pp 500-520.

(29) Lebkisher, R. et al (1965) "Aramco Handbook". Arabian American Oil Company.

(30) Lees, G.M. (1928) "The Physical Geography of South-East Arabia Geog. J., Vol. 71, pp 441-470.

(31) McCann, D.L. (1959) "Upper Wadi Hanifah Water Resources". Unpublished Report prepared for the Ministry of Agriculture, Riyadh.

(32) Ministry of Agriculture and Water (1964) "Agricultural Survey of the Central Area of Saudi Arabia". Unpublished Statistic filed in the Department of Statistic and Agricultural Economy, Riyadh.

(33) ------------- (1971) "The Green Deserts". Unpublished mimeograph filed in the Division of Guidance and Agricultural Services, Riyadh, (in Arabic)

(34) ------------- (1973) "Agricultural Guidance Bulletin". Vol. 5, No. 3, (in Arabic)

(35) ------------- (1973) "Composite Well Log-- Salboukh No. 2". "Composite Well Log - Salboukh No. 3". "Composite Well Log - Salboukh No. 4". Maps No. 5 R3/4/5, filed in the Department of Geology, Riyadh.

(36) Ministry of Labour and Social Affairs (1964) "Social Development in the Kingdom of Saudi Arabia". Unpublished Mimeograph, Riyadh, (in Arabic)

(37) Ministry of Petroleum and Mineral Resources (1967) "Aerial Photographs of Najd Area". Sheets No. 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16. Aerial Survey Department, Riyadh.

(38) Mishari, H. (1967) "Towards Full Water Utilization in Saudi Arabia". Water for Peace Conference, Washington, D.C., 1967.

(39) Nouri, M. (1967) "Water Control in Saudi Arabia". Unpublished Report filed in the Department of Geology, Ministry of Agriculture and Water, Riyadh, (in Arabic)

(40) ------------- (1974) "The Aquifers of Saudi Arabia: A Study of Their Extents, Development and Extractions". Unpublished Report filed in the Department of Geology, Ministry of Agriculture, Riyadh, (in Arabic)

(41) Otkun, G. (1968) "Ground Water in Saudi Arabia". Report filed in the Department of Geology. Ministry of Agriculture and Water, Riyadh.

(42) ------------- (1970) "Some Aspects of Ground Water Distribution and Exploration in Saudi Arabia". Report filed in the Department of Geology, Ministry of Agriculture, Riyadh.

(43) Pakistan Technical Survey Mission (1954) "Report of the Pakistan Technical Survey Mission". Unpublished Report prepared for the Government of Saudi Arabia, Riyadh.

(44) Philby, H. St. J.B. (1922) "The Heart of Arabia". London, 1922.

(45) Powers et al (1966) "Geology of the Arabian Peninsula - Sedementary Geology of Saudi Arabia". Geological Survey Professional Paper 560-D, United State Government Printing Office, Washington.

(46) Quimpo, J.S. (1972) "Water Level in Minjur at Riyadh". Unpublished Report filed under No. 389/106/9211, Water Resources Division, Ministry of Agriculture and Water, Riyadh.

(47) Ralf M. Parsons Engineering Company (1958) "Preliminary Report on Hayir Water System". Unpublished Report prepared for the Ministry of Agriculture, Riyadh.

(48) Riyadh Airport "Meteorological Data of Riyadh Airport between 1953 and 1971". Data filed in the Meteorology Department, Riyadh.

(49) Shaikh, A.K. (1972) "Preliminary Reconnaisance Report on Proposed Ha'ir Dam Site". Unpublished Report filed under No. 96/107/923, Water Resources Division, Ministry of Agriculture and Water, Riyadh, (in Arabic)

(50) Sogreah (1967) "Riyadh Water Supply". Unpublished Report prepared for the Ministry of Agriculture and Water of Saudi Arabia, Grenoble, France

(51) -------------- (1968 A) "Water Resources - Area V". Unpublished Report prepared for the Ministry of Agriculture and Water of Saudi Arabia, Grenoble.

(52) -------------- (1968 B) "Riyadh Deep Well". Unpublished Report prepared for the Ministry of Agriculture and Water of Saudi Arabia, Genoble

(53) -------------- (1968 C) "Agriculture and Grazing Potential - Area V". Unpublished Report prepared for the Ministry of Agriculture and Water of Saudi Arabia, Grenoble.

(54) -------------- (1968 D) "Observations - Area V". Unpublished Data carried out between 1966 and 1968, prepared for the Ministry of Agriculture and Water of Saudi Arabia, Grenoble.

(55) Steineke, M. and Bramkamp, R.A. (1952) "Mesozoic Rocks of Eastern Saudi Arabia". Bull. Amer. Assoc. Petrol Geologists, Vol. 36, p 909.

(56) U.S. Geological Survey (1958) "Geology of the Northern Tuwayq Quadrangle, Kingdom of Saudi Arabia". Miscellaneous Geologic Investigations, Map 1-207 A, Scale 1 : 500,000.

(57) V.B.B. (1965) "The Project of Treatment and Distribution of Riyadh Water Supply". Unpublished Report prepared for the Ministry of Agriculture and Water, Riyadh.

(58) Wahbah, H. (1946) "Arabian Peninsula in the 20th Century". Cairo, (in Arabic).

(59) Ward, R.C. (1957) "Principles of Hydrology". McGraw - Hill Publishing Company Ltd., London, New York, Toronto, Sydney.

(60) Wilson, A.T. (1928) "The Persian Gulf". Oxford, 1928.

(61) Wilson, G. (1953) "Riyadh Water Supply". Unpublished Report prepared for the Ministry of Agriculture, Riyadh.

(62) Wolfart, R. (1961) "Geologic-Hydrologic Research for the Utilization of Ground Water in the Wadi Nisah Area". Unpublished Report prepared for the Ministry of Agriculture of Saudi Arabia, Hanover.

II - Consulted Bibliography

(1) Al-Blehed, A. (1975) "Contribution to the Climate Studies on Saudi Arabia". M.Sc. Thesis, The Geography Department, University of Durham, England.

(2) Al-Khameis, A. (1970) "The Road between Al-Yamamah and Al-Hijaz". Dar Al-Yamamah, Riyadh, (in Arabic)

(3) Allered, B.W. et al (1965) "Ecological Evaluation of Plants, Saudi Arabia". Typed Publication Project 117, FAO, Rome.

(4) Aramco (1962) "The Evolution of known Clay Deposits in Al-Kharj and the Eastern Province of Saudi Arabia". Aramco Contact No. 1301-0030. Al-Khober.

(5) Bagnold, Brigadier R.A. (1951) "Sand Formation in Southern Arabia". Geog. J., Vol. 117, pp 78-82.

(6) Bannon, J.K. (1954) "Note on the Structure of the High Altitude Strong Wind Belt in the Middle East in Winter". Quat. Jour of the Roy. Meteo. Soc., Vol. 80 pp 218-221.

(7) Baumer, M. (1964) "Scientific Research aimed at Developing the Arid Zone of Saudi Arabia". Typed Mimeograph, NS/AZ/754, UNESCO, Paris.

(8) Beaty, C.B. (1971) "Climate Change: Some Doubts". Bull. Geol. Soc. of America, Vol. 82, pp 1395-1397.

(9) Beaumont, P. (1974) "New Uses for Ancient Water". The Financial Times, London, June 10th, 1974.

(10) Beaumont, P. et al (1975) "The Middle East: A Geographical Study". John Wiley & Sons, London, New York, Sydney, Toronto.

(11) Beckchourin, S. (1961) "Hydrology of Irrigated Lands". Foreign Languages Publication, Moscow.

(12) Brown, G. (1960) "Geomorphology of Western and Central Saudi Arabia". Rep. 21st Int. Geol. Cong., part 21, pp 150-159, Copenhagen.

(13) Burdon, D.J. (1950) "Ground Water Development at Riyadh". Unpublished Report prepared for the Ministry of Agriculture, Riyadh.

(14) Burdon, D.J. and Otkun, G. (1968) "Hydrological Control of Development in Saudi Arabia". Inter. Geol. Cong., Vol. 12, pp 145-153.

(15) Burdon, D.J. et al (1971) "Ground Water's Role in Social and Economic Development : An example based on FAO Near East Regional Activities on Ground Water Development and Use". Paper prepared to the Conference on (Hydrology and Hydrometeorology in the Economic Development of Africa), Addis Ababa,

(16) Burdon, D. (1973) "Ground Water Resources in Saudi Arabia". Ground Water Resources in Arab Countries, Science Monograph No. 2.

(17) Butzer, K.W. (1957) "Late Glacial and Postglacial Climate Variation in the Near East". Erdkunde, Vol. 11, pp 21-35.

(18) Champon, R.W. (1971) "Climatic Changes and the Evolution of Landform in the Eastern Province of Saudi Arabia". Bull. Geol. Soc. of America, Vol. 82, pp 2713-2727.

(19) Chorley, R.J. (edit.) (1971) "Introduction to Geographical Hydrology". Methuen & Co. Ltd., London.

(20) Chorley, R.J. (edit.) (1971) "Introduction to Physical Hydrology". Methuen & Co. Ltd., London.

(21) Crary, D.D. (1951) "Recent Agricultural Development in Saudi Arabia". Amer. Geog. J. Vol. 41, pp 366-388.

(22) Cressey, G.B. (1957) "Water in the Desert". Annals of the Association of American Geographers, Vol. 47, pp 105-124.

(23) Cressey, G. (1960) "Crossroads : Land and Life in South-west Asia". J.B. Lippincott Co., Chicago, New York, Philadelphia.

(24) Davis, R. (1959) "Preliminary Master Plan for Water Resources Development in Saudi Arabia". Unpublished Report prepared for the Ministry of Agriculture, Ralf M. Parsons Engineering Co., Riyadh.

(25) Davis, R. and Bahta, M. (1961) "Report about Drilling for Agricultural Purposes". Unpublished Report filed in the Geology Department of the Ministry of Agriculture and Water, Riyadh, (in Arabic).

(26) Davis, S.N. and De Wiest, J.M. (1966) "Hydrogeology". John Wiley & Sons, Inc., New York, London, Sydney.

(27) Davis, W.M. (1905) "The Geographical Cycle in an Arid Climate". Jour. Geol. Vol. 13, pp 381-407.

(28) Dincer, D. et al (1974) "Study of the Infiltration and Recharge through the Sand Dunes 1 in Arid Zones with Special Reference to the Isotopes and Thermonuclear Tritium". Jour. of Hydrology, Vol. 23, pp 79-1o9.

(29) Dodd, A.V. (1965) "Some Aspects of the Climate of Southwest Asia". Meteo. Magazine, Vol. 94, pp 38-47.

(30) Dougherty, D. and Wilson, G.R. (1953) "The Water Supply of Riyadh, Saudi Arabia". Unpublished Report prepared to the Government of Saudi Arabia, Riyadh.

(31) Dresch, J. (1966) "Utilization and Human Geography". Institute of British Geographers. Translation No. 40, George Phillip & Son Ltd., London.

(32) Droubin, G. et al (1963) "Report to the Government of Saudi Arabia on Future Prospects for Hydro-Agricultural Development". Typed EPTA Report No. 1638, FAO, Rome.

(33) FAO (1958) "Agriculture Extension in Saudi Arabia". Typed EPTA Report No. 518.

(34) Furn, R. (1967) "The Problems of Water : A World Study". Faber & Faber, London

(35) Gresswell, R. (1970) "Physical Geography". Longman Group Ltd., London.

(36) Halm, H.M. (1955) "The Agricultural Resourced of the Arabian Peninsula". Unpublished Mimeograph, U.S.D.A., Washington.

(37) Heady, H.F. (1963) "Report to the Government of Saudi Arabia in Grazing Resources and Problems". Typed ETEP Report No. 1614, FAO, Rome.

(38) Holm, D.A. (1960) "Desert Morphology in the Arabian Peninsula". Science Vol. 132, pp 1369-1379.

(39) Kassa, M. and Imam, M. (1954) "The Wadi Ecosystem". Jour. Ecol., Vol. 42, pp 424-441.

(40) Levi, W.M. (1963) "The Dry Winter of 1962/63 : A Synoptic Analysis". Israel Exploration J., Vol. 13, pp 229-241.

(41) Maktari, A.M.A. (1971) "Water Rights and Irrigation Practices in Lahj : A Study of the application of customary and Shariah Law in Southwest Arabia". Oriental Publication No. 21, Cambridge University Press.

(42) Manners, Ian R. (1971) "The Desert and the Sown : An Ecological Appraisal of the Middle East". Focus, Vol. 22, November 1971.

(43) McGinnies, W.G. et al (edit.) (1968) "Deserts of the World : An Appraisal of Research into their Physical and Biological Environments". University of Arizona Press.

(44) Ministry of Agriculture and Water (1964) "Economic Studies on Agriculture in Saudi Arabia". Typed Report filed in the Department of Agricultural Economic and Statistics.

(45) Ministry of Agriculture and Water (1972) "Water Table Observations at Some Wells in the Wadi Hanifah". Data prepared by the Hydrology Department, Riyadh.

(46) Mitchel, W.A. (1971) "Movement and Pastoral Nomadism : A Tentative Model". The Rocky Mountains Social Science J., Vol. 8, pp 63.71.

(47) Newton, R.B. (1921) "On a Marine Jurassic Fauna from Central Arabia". Ann. & Mag. N. Hist., Vol. 7, pp 389-403.

(48) Oppenheimer, H.R. (1950) "Summer Drought and Water Balance of Plants Growing in the Near East". The Seventh International Botanic Congress, Stockholm.

(49) Otkun, G. (1971) "Paleozoic Sandstone Aquifers in Saudi Arabia". Paper published in Memoires of I.A.H. Symposium, Tokyo, 1971.

(50) Otkun, G. (1971) "Report about the Wells in the Farm of HRH Prince Talal Bin Abdul Aziz in Wadi Hanifah". Unpublished Report No. 416/71/11/91, filed in the Geology Department, the Ministry of Agriculture and Water, Riyadh, 1971, (in Arabic)

(51) Otkun, G. (1972) "Observations on Mesozoic Sandstone Aquifers in Saudi Arabia". 24th Int. Geol. Cong., Section 11, pp 28-53.

(52) Pedgley, D.E. (1969) "Cyclones along the Arabian Coast". Weather Vol. 24, pp 456-469.

(53) Philby, H. St. J.B. (1949) "Two Notes from Central Arabia". Geog. J., Vol. 113-114, pp 86-92.

(54) Philby, H. St. J.B. (1952) "Arabian Highlands". London,

(55) -------------- (1955) "Saudi Arabia". London.

(56) Philby, H. St. J. (1972) "Rub'al Kjali". Geog. J., Vol. 82, pp 1-33.

(57) Picard, L. (1937) "On the Structure of the Arabian Peninsula". Bull. Hebrew University, Jerusalem, Section 1, pp 3-12.

(58) Popenoe P. (1962) "The Distribution of the Data Palm". Amer. Geog. J., Vol. 16, pp 117-121.

(59) Quimpo, J. (no date) "Report about the Wells of HRH Prince Nayef Ibn Abdul Aziz in Wadi Hanifah". Unpublished Report filed in the Geology Department, the Ministry of Agriculture and Water, Riyadh.

(60) Qurashi, A. Iqbal (1956) "Basic Facts about Saudi Arabia". Typed Report prepared for the Ministry of Finance and National Economy.

(61) Romeyrol, R. (1968) "Nubian Sandstone". Bull. Amer. Assoc. Petrol Geologists, Vol. 52, pp 589-600.

(62) Sayigh, Y.A. (1971) "Problems and Projects of Development in the Arabian Peninsula". Internation J. of Middle East Studies., Vol. 2, pp 40-59.

(63) Shafi, A. (1953) "Preliminary Report on Water Resources in Wadi Hanifah, Neighbouring Wadis and New Water Supplies for Riyadh". Unpublished Report prepared for the Government of Saudi Arabia, Riyadh

(64) Shaikh, A.H. (1971) "The Majmaah Dam, Saudi Arabia". Water and Water Eng., Vol. 75, p 70.

(65) Smith, C.G. (1970) "Water Resources and Irrigation in the Middle East, Geography, Vol. 50, pp 407-425.

(66) Stevens, J.H. (1972) "Oasis Agriculture in the Central and Eastern Arabian Peninsula". Geography, Vol. 57, pp 321-326.

(67) Thatcher, L. et al (1961) "Dating Desert Ground Water". Science, Vol. 134, pp 105-106.

(68) Thornthwait, C.W. (1948) "An Approach Towards a Rational Classification of Climate". The Geog. Rev., Vol. 38, pp 55-94.

(69) Twitchel, K.S. (1944) "Water Resources of Saudi Arabia". Amer. Geog. Rev., Vol. 34, pp 364-386.

(70) Twitchel, K.S. and Jurgi, E. (1952) "Saudi Arabia, with an Account of Development of its Natural Resources". New Jersey, Princeton.

(71) Tylor, A. (1966) "Saudi Arabia". Focus, Vol. 16, May 1966.

(72) U.N.E.S.C.O. (1953) "Reviews of Research in Arid Zone Hydrology". Arid Zone Research Series No.1

(73) -------------- (1959) "Arid Zone Hydrology : Recent Development". Arid Zone Research Series No. 12.

(74) -------------- (1962) "The Problems of the Arid Zone : Proceeding of the Paris Symposium". Arid Zone Research Series No. 18.

(75) V.B.B. (1971) "The Project of Distribution and Treatment of Riyadh Water Supply". A Report to the Ministry of Agriculture and Water, Stockholm, Sweden.

(76) Wells, M.J. (1966) "New Assessment of Saudi Arabian Water Resources have high Potential". Wld. Petrol., Vol. 37, p 14.

(77) White, G.F. (edit) (1961) "Flood Porblems ". Department of Geography, Research Paper No. 70, University of Chicago, Illinois.

(78) Zaghloul, F.H. (1963) "The Scope of Community Water Supply in Saudi Arabia". Typed Report prepared for the Ministry of Health, Riyadh.